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GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION

PROJECT INITIATION

Date: 25 August 1975

Project Title: Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design

Project No.: A-1757

Project Director: J. N. Harris

Sponsor: Black & Veatch

Agreement Period: From 1 July 1975 Until 27 September 1975*

Type Agreement: Letter contract dated 14 July 1975 (Subcontract under EPRI Prime Contract 750605)

Amount: $22,991 (Total anticipated funding $54,424)

Reports Required: Interim

Sponsor Contact Person:

H. W. Strohm, Project Administrator
Black & Veatch, Consulting Engineers
P. O. Box 8405
Kansas City, Missouri 64114

Telephone: 816/361-7000

*Execution of Definitive Contract anticipated by 27 September 1975.
Total contract period anticipated - 14 months.

Assigned to: EES - EMTD

COPIES TO:

Project Director	EES Supply Services
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	Other Sue Corbin; Bonnie Wettlaufer

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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: 12/6/76

Project Title: Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design.

Project No: A-1757

Project Director: J. N. Harris

Sponsor: Black and Veatch, Consulting Engineers, Kansas City, Missouri 64114

Effective Termination Date: 7/10/76

Clearance of Accounting Charges: 7/31/76

Grant/Contract Closeout Actions Remaining:

_ Final Invoice and Closing Documents
_ Final Fiscal Report
_ Final Report of Inventions
_ Govt. Property Inventory & Related Certificate
_ Classified Material Certificate
_ Other ______________

Assigned to: Applied Sciences Laboratory (School/Laboratory)

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CA–4 (3/76)

A-1757

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

August 1, 1975

Black and Veatch
P. O. Box 8405
Kansas City, MO 64114

Attention: J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 1, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design", Black and Veatch Project 6983, Ga. Tech Project A-1757.

I. INITIATION OF SUBTASKS

The contract was initiated July 1, 1975 and this is the first interim progress report. A meeting of personnel from Black and Veatch, Honeywell and Georgia Tech was held on Tuesday July 8, 1975 at Black and Veatch to discuss the program and coordinate the activities of each of the participants. A decision was made to initially investigate two cavity geometries. The first geometry would be a parallel arrangement of tubes radiantly heated on the outside with air flowing inside the tubes. This configuration will be described as, "Tubed Heat Transfer Cavity". The second geometry to be considered will be an arrangement of tubes in a circular arch (dome shape). These tubes are to be heated by solar radiation entering the open end of the tubes. Heat will be transferred by air passing over the outside surfaces of the tubes. Henceforth, this configuration will be described as, "Extended Surface Heat Transfer Cavity".

1. Subtask 1.2, Cavity Geometry

At the meeting at Black and Veatch on July 8 and 9, 1975, Dr. Ed McBride of Black and Veatch and Dr. Steve Bomar of Georgia Tech agreed to conduct feasibility calculations on the two proposed designs. It was agreed that Georgia Tech would use existing computer programs and some supporting calculations to determine size and feasibility of a "Tubed Heat Transfer Cavity". Dr. McBride will determine the size and feasibility of the "Extended Surface Heat Transfer Cavity".

2. Approach Taken in the Work

A concentration factor of 200 was assumed (57,080 Btu/hr ft^2). Aluminum oxide tubes were assumed standing 1.5 tube diameters in front of a diffusely reflecting wall. Heat flux was calculated for 16 circumferential positions from front to back (0 to 180^{o}) of the tube. These data were used for three separate cases for the thermal analysis program: conditions at the tube entrance, conditions in the middle and conditions at the tube exit.

Tube diameter, fluid temperature, convective coefficient, tube absorptivity, tube conductivity and assumed boundary layer temperature conditions used are shown in Table I.

TABLE I.

INPUT PARAMETERS FOR THERMAL ANALYSIS PROGRAM

Inside Diameter (in)	Fluid Temp. (^{o}F)	Convective Coeff. (Btu/hr ft^{2} ^{o}F)	Tube Absorptivity	Tube Conductivity (Btu/hr ft ^{o}F)	Assumed Boun. Layer Temp. (^{o}F)
1.00	800	34.3	1.0	5.5	1100
1.00	1300	28.6	1.0	4.0	1700
1.00	1800	26.9	1.0	3.4	2000
3.00	800	27.5	1.0	5.5	1100
3.00	1300	23.0	1.0	4.0	1700
3.00	1800	21.6	1.0	3.4	2000

NOTE: fluid velocity is assumed to be 100 ft/sec in the tubes

The output data was used to calculate heat transferred per unit area of tube so as to arrive at total tube length needed for a one megawatt bench model system.

Stress calculations were also made using a gas pressure of 60 psia and data in the literature for elastic modulus and thermal expansion coefficient with respect to temperature and Poisson's ratio of aluminum oxide.

3. Summary of Results

The results for one inch and inside diameter tubes are summarizes in Table II.

TABLE II.

THERMAL DATA FOR ALUMINUM OXIDE TUBES IN TUBED HEAT TRANSFER CAVITY CONFIGURATION

TUBE INSIDE DIAMETER	LOCATION	AVG. INSIDE WALL TEMP. (°F)	MAX. INSIDE WALL TEMP. (°F)	T FRONT TO BACK (°F)	AVG. Q/L TO FLUID (Btu/hr-ft)	INDIVIDUAL TUBE LENGTH (ft)	TOTAL TUBE LENGTH FOR 1 MW MODEL (ft)	NO. OF TUBES FOR 1 MW MODEL (No.)
One Inch 0.042 Wall	Entrance	1,608	2,311	1,008	7,251			
	Mid-Point	2,274	3,120	1,215	7,294	2.3	468	203
	Exit	2,839	3,748	1,305	7,315			
Three Inch 0.125 Wall	Entrance	1,824	2,806	1,390	22,138			
	Mid-Point	2,533	3,720	1,685	22,278	6.8	153	23
	Exit	3,116	4,394	1,814	22,326			

NOTE: (1) Tube Distance from tube center to diffusely reflecting wall 1.5 tube diameters.
(2) Tube spacing center to center 2 tube diameters.

It should be noted that in these calculations maximum inside wall temperature exceeds the melting point of aluminum oxide at the exit point on one inch tubes and at the mid and exit points on three inch tubes. However, these conditions are for an absorptivity of one which will not be the actual case with aluminum oxide tubes.

Stress calculations were made on the one inch diameter tubes for two conditions; (1) the tubes were free to expand in any direction and (2) the tubes were confined to a plane. Stress calculations on the three inch diameter tubes were made only for tubes free to expand in any direction. The worse stresses were longitudinal. The maximum compressive stress for the one inch tubes free to expand was 72,705 psi. Maximum tensile stress was 85,267 psi. For the three inch tube maximum compressive and tensile values were 116,075 and 136,281 psi respectively and occurred at the mid-point of the tubes. In the case of the one inch tube, stresses were not calculated for the condition of a confined plane at mid-point. Maximum stresses at the exit were 176,770 psi compressive and 78,779 psi tensile.

These stresses are not considered to be typical of actual conditions because of: the asymmetric heating conditions used in the computer program and due to the use of surface absorptivity of one. Experimental data from the tube test facility now under construction should provide input to the computer programs for more realistic conditions.

II. SUBTASKS NOT COMPLETED BUT IN PROGRESS

Subtask 3.0 Preliminary Performance Tests

Design and construction of a quartz lamp heated test facility were initiated. This facility will have the capability of providing temperature data on ceramic tubes up to 16 inches in length. Preliminary estimates indicate that air temperature through a one inch diameter alumina tube can be increased on the order of 350°F from entrance to exit of its 16 inch length using the available quartz lamp bank. An air preheater is being designed to provide entrance air up to 1800°F. A block diagram of the layout of the test facilities is attached to this report. Temperature sensors are built into the ceramic tube holders but are not shown in the diagram. Detailed drawings of the facility are now being prepared.

The quartz lamp bank has been installed on a universal mounting which will allow considerable latitude in adjustment. Electrical power leads and coolant water lines have been installed. An air supply has been piped to the room housing the facility.

The initial alumina tubes to be tested and other ceramic tubes to be used as tube holders have been ordered. The facility is approximately 30 percent completed and no problems are foreseen in completing this facility on schedule.

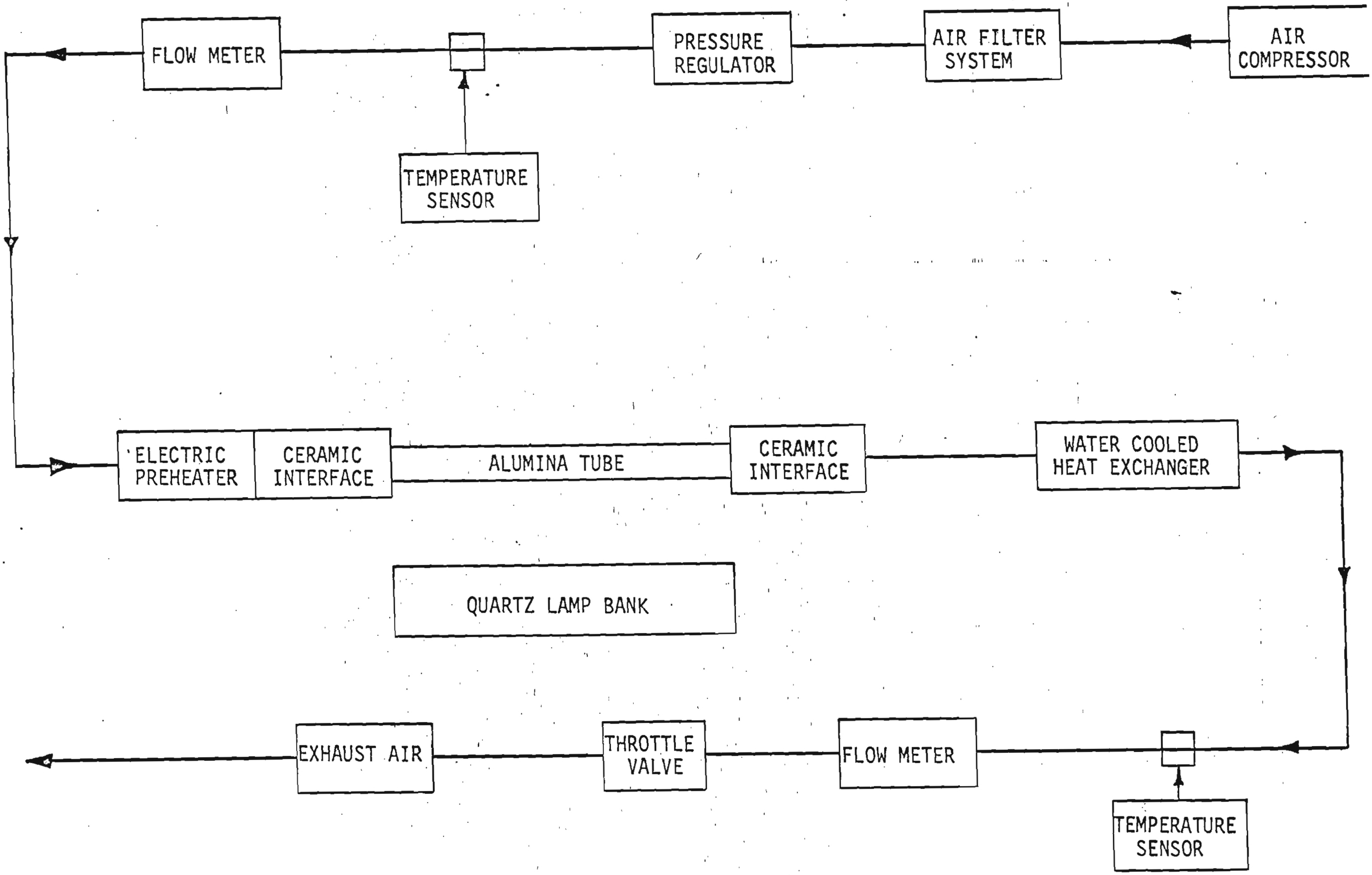
III. CHANGES IN PROJECT PERSONNEL

Mr. J. D. Walton, Jr. the original proposed project director begins a 7 month leave of absence on August 1, 1975. Mr. Joe N. Harris will be the Ga. Tech project director on this program.

Respectfully Submitted,

J. N. Harris
Project Director

BLOCK DIAGRAM OF CERAMIC HEAT EXCHANGER TUBE
TEST FACILITY



A-1757

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

August 29, 1976

Black and Veatch
P. O. Box 8405
Kansas City, MO 64114

Attention: J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 2, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design," Black and Veatch Project 6983, Ga. Tech Project A-1757.

Gentlemen:

Mr. J. N. Harris attended the August 22, 1975 EPRI "kick off meeting" on this program and presented reports of the work on heat transfer calculation on tube type receivers and on the progress of the infrared quartz lamp radiant test facility.

During this trip to Palo Alto it was agreed that at least two ceramic materials would be tested as single tubes in the radiant test facility. These materials are aluminum oxide and silicon carbide. It is anticipated that aluminum oxide tubes will be tested first and tubes from more than one manufacturer will be tested. It was further agreed that, if time and funds permit, tests will be performed on Pyroceram® and fused silica tubes. In conjunction with the preparation for these tests a preliminary test plan was submitted to Black and Veatch on August 26, 1975 so that it could be available for a meeting between Black and Veatch and Honeywell on August 27, 1975. A refined and more detailed test plan will be submitted at a later date.

Technical Status by Task

Task 2.2 Heat Exchanger Configuration. In interim progress report No. 1 thermal data were presented for aluminum oxide tubes of one inch and three inch diameter equally irradiated at the entrance, mid-point and exit end of the tubes. The wall temperature and the longitudinal thermally induced stress exceeded the capabilities of aluminum oxide for these conditions. Therefore, conditions were changed to investigate a variable heat flux along the tubes. Variable heat fluxes of 200, 100 and 50 suns and 100, 50 and 25 suns were used at the entrance, mid-point and exit respectively. All other input parameters were the same as for the previous calculations (Table I interim report No. 1). Table I give maximum temperature and stress data for these conditions for tubes free to expand longitudinally, but constrained in all other directions.

TABLE I

THERMAL AND STRESS DATA FOR ONE INCH DIAMETER ALUMINUM OXIDE TUBES IN A TUBE TYPE RECEIVER

Heat Flux (suns)	Location	Maximum Wall Temperature (^{o}F)	Maximum Longitudinal Tensile Stress (psi)
200	Entrance	2346	76,620
200	Mid-point	----	------
200	Exit	3804	78,780
200	Entrance	2350	58,820
100	Mid-point	2260	43,140
50	Exit	2320	28,610
100	Entrance	1590	32,470
50	Mid-point	1790	25,410
25	Exit	2070	17,280

Two other "limiting" cases were also examined. These were: (1) an optimized tube spacing with tubes spaced five diameters apart and standing 1.5 diameters in front of a diffusely reflecting wall, and (2) a uniform (symmetric flux) of 100 suns on a tube. These data were run for entrance conditions only and are given in Table II. Since aluminum oxide has a nominal tensile strength of 45,000 psi and a melting point of 3650^{o}F. Any tensile stress greater than 30,000 psi was considered too much stress and wall temperature should be limited to 2,500^{o}F or less. The only two cases examined coming close to meeting these two requirements were: (1) the uniformly heated tube (which cannot be achieved with the current design) and (2) the low variable flux from entrance to exit. The computer codes are now being modified to examine silicon carbide, fused

TABLE II

LIMITING CASES ON ONE INCH DIAMETER ALUMINUM OXIDE TUBES

Case	Heat Flux (suns)	Location	Maximum Wall Temperature (^{o}F)	Maximum Longitudinal Tensile Stress (psi)
Symmetrical	100	Entrance	1600	3,048
Optium Tube Spacing	200	Entrance	2350	59,360

silica and Pyroceram®. Computer runs are also being made for aluminum oxide with fluid flows of other than 100 ft/sec. However, none of these data were completed in time for inclusion in this report.

Task 3.1 Experiment Design. The quartz lamp heated test facility is approximately 85 percent completed. However, there may be some short delays in completion due to delays within the machine shop. Both aluminum oxide and silicon carbide tubes, one inch in diameter have been ordered for test purposes. It is now anticipated that the first testing will be started about October 1, 1975.

Financial Status

A copy of the appropriations statement for the month of July was provided to Mr. Hans Strohm on August 21, 1975. The financial status for August will not be available until approximately the tenth of the month.

Respectfully Submitted,

J. N. Harris
Project Director

A-1757

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

September 30, 1975

Black and Veatch
P. O. Box 8405
Kansas City, MO 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 3 "Solar Thermal Conversion to Electricity Utilizing a Central Receiver Open Cycle Gas Turbine Design," Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

Dr. J. C. Grosskreutz and Dr. E. J. McBride of Black and Veatch visited Georgia Tech on September 8, 1975. The following subjects were discussed:

(1) The computer codes and methods used to calculate temperatures and stresses on the tubes in a tubed heat exchanger configuration

(2) Evolution of a test plan to present to EPRI for the ceramic materials testing and test configurations to be examined

(3) The constructability/fabricability of large ceramic heat exchangers.

As a result of this meeting it was decided that Georgia Tech would not make any further heat transfer or stress calculations. Card decks were shipped to Dr. Ed McBride for two programs designated TEMP. and STRESS. These card decks were developed to run on the Georgia Tech Univac 1108 computer and will require some modification to run on the Black and Veatch equipment. A new test plan for the quartz lamp radiant test facility was developed and was submitted to Black and Veatch for further submission to EPRI. A study of the constructability/fabricability of large ceramic heat exchangers of the tube type or extended surface type was initiated, however, the anticipated start time was delayed by approximately ten days due to prior commitments of the assigned engineer's time. This study is now in progress and the initial report will be made during the first or second week of October.

On Wednesday, September 24, 1975, Mr. J. N. Harris of Georgia Tech visited Hague International in Portland, Maine to discuss the development of ceramic heat exchanger tubes. A separate report on this visit has been prepared and submitted to Black and Veatch. On Wednesday evening, Mr. Harris joined Mr. John Kintigh and Mr. Don Gray of Black and Veatch and Mr. Joe Studniarz of General Electric in Schenectady, New York to visit the General Electric gas turbine operations in Schenectady and in Greenville, South Carolina.

Technical Status by Task

Task 2.2 Heat Exchanger Configuration

The computer codes used to calculate temperatures and stresses for aluminum oxide under various heat flux conditions were modifed to examine one inch diameter fused silica, silicon carbide, Pyroceram and cordierite tubes uniformly heated with a flux of 200 suns (asymmetric heating at entrance midpoint and exit end of tube) and an air velocity of 100 ft/sec. Data for maximum wall temperature and maximum tensile stress are given in Table I. In each case wall temperatures are excessively high and stresses are too high except for fused silica. Either fluid velocity must be increased, heat flux reduced, or both to bring temperatures and stresses to acceptable levels.

Computer calculations were also made for one inch diameter aluminum oxide tubes with air velocities of 140 and 200 ft/sec. These results are given in Table II. As can be seen the increased velocity reduces wall temperature and tensile stress, but the stress is not reduced to an acceptable level even with an air velocity of 200 ft/sec.

A study was initiated to determine the problems in construction of tubed and extended surface heat exchangers. Data and recommendations from this study will be available in the next report period.

Task 3.1 Experiment Design

Tests to be conducted were modified during the visit of Dr. Grosskreutz and Dr. McBride. A simple method was suggested for measuring emissivity and reflectance of flat plates of the ceramic materials to be tested. After discussions with Dr. C. W. Gorton of Georgia Tech it was decided that values obtained by the suggested method might not be sufficiently accurate due to temperature measurement problems and convection losses. Contact has been made with Mr. Gerald Brown of the Thermophysics section of TRW, One Space Park, Redondo Beach, California, concerning the required measurements. He is sending literature and price schedules for the necessary tests. Based on sample geometry required, costs of testing and data output to be received, a decision will be necessary as to whether these tests are to be run.

Due to modifications in the test plan some modifications in the test set-up were necessary and some additional materials were ordered. Some extended delays in the EES Shop have pushed back the completion date of the test facility. It is presently estimated that the facility will be operational between October 15 and October 22, 1975, and pending approval of the test plan by EPRI the first tube tests can begin.

Financial Status:

A financial report on the status of expenditures as of 31 August was mailed to Mr. Hans Strohm on September 15, 1975. A financial status report as of 30 September will be forwarded to Mr. Strohm as soon as the September appropriations statements are received from accounting.

Respectfully submitted,

Joe N. Harris
Project Director

jw

TABLE I

MAXIMUM WALL TEMPERATURE AND TENSILE STRESS DATA FOR ONE INCH DIAMETER CERAMIC TUBES IN A TUBE TYPE RECEIVER WITH AIR FLOW OF 100 FEET PER SECOND THROUGH TUBE

Type Material	Location On Tube	Max. Wall Temperature (^oF)	Maximum Longitudinal Tensile Stress (psi)
Fused Silica	Entrance	2643	1,450
	Mid-Point	3375	1,499
	Exit	3867	1,379
Silicon Carbide	Entrance	2032	36,532
	Mid-Point	2754	41,862
	Exit	3389	43,921
Pyroceram	Entrance	2540	22,772
	Mid-Point	3357	26,140
	Exit	3976	27,361
Cordierite	Entrance	2585	11,280
	Mid-Point	3392	12,714
	Exit	4007	13,229

Note: (1) All tubes one inch inside diameter, 0.042 inch wall thickness, heat flux 200 suns at entrance, mid-point, and exit, fluid temperature 800^o, 1300^o and 1800^o F at entrance, mid-point and exit respectively.

(2) These conditions produce excessive wall temperatures at the exit in all cases. Either fluid flow must be increased or radiant flux decreased to bring wall temperatures within acceptable limits.

TABLE II

TEMPERATURE AND STRESS DATA FOR ONE INCH DIAMETER ALUMINUM OXIDE TUBES IN A TUBE TYPE RECEIVER SUBJECTED TO A HEAT FLUX OF 200 SUNS AT ENTRANCE MID-POINT AND EXIT END OF TUBES

Fluid Velocity (fps)	Location On Tube	Max. Wall Temperature (^oF)	Maximum Longitudinal Tensile Stress (psi)	Tube Length Required (ft)	No. of Tubes For 1 MWth
100	Entrance	2311	76,620	2.3	203
	Mid-Point	3120	---		
	Exit	3748	78,780	2.3	203
140	Entrance	2022	59,065		
	Mid-Point	2776	76,444		
	Exit	3383	73,893	3.2	145
200	Entrance	1750	47,947		
	Mid-Point	2450	63,964		
	Exit	3033	66,333	4.6	102

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

November 4, 1975

Black and Veatch
P. O. Box 8405
Kansas City, Missouri 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 4, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver Open Cycle Gas Turbine Design," Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

Work was conducted during this report period on Task 2.2 "Heat Exchanger Configuration" and on Tasks 3.1 and 3.2 "Experiment Design Fabrication and Instrumentation." Under Task 3.2 work was continued on the assembly of components for the radiant test facility to be used to conduct the tests outlined in the test plan submitted to Black and Veatch on September 15, 1975. In addition, information was received from TRW Systems Group on their capabilities to make thermal radiation property measurements on materials.

On Task 2.2 methods of fabricating the ceramic heat exchanger were considered and surveys were conducted to find existing large high temperature ceramic facilities.

On October 22, 1975, a review meeting was held at Black and Veatch to discuss:

(1) Progress of the test program

(2) Additions to the test plan

(3) Heat transfer results

(4) Heat exchanger fabricability study

(5) Evaluation of heat exchanger objectives

(6) Objectives for EPRI review on November 14, 1975.

As a result of discussions during this meeting the following input parameters were evaluated by Black and Veatch for a bull's-eye opening tubed heat exchanger utilizing "hairpin" shaped silicon carbide tubes 40 feet in length and 4 inches O. D. with 1/8 inch walls. The legs of the hairpin are spaced 3 diameters center line to center line. The cavity opening is 25 feet in diameter and the cavity is 40 feet in diameter or 40 feet on a side.

Using these parameters preliminary sketches were made on joining ceramic (SiC) tubes, elbows and metal to ceramic seals at the header. These sketches and sketches of a ceramic tile to form the web of an extended surface heat exchanger were submitted to Black and Veatch on October 31, 1975 along with data on properties of silicon carbide and two possible metals, "HX and Hasteloy X" for use as a header. In further discussions, "Haynes 188" and "Inconel 617" were suggested by Dr. Grosskreutz as tentative header materials.

Information is being obtained for a recommendation on a ceramics manufacturing consultant. At this point it is considered that two consultants may be required; one who is an expert on the ceramic material fabricability (SiC or Al_2O_3) and one who is experienced in construction of large ceramic structures. At this time two contacts have been made, these are Dr. Edwin Kraft of the Carborundum Company, Niagara Falls, New York, and Mr. Francis Pixley of Mine and Smetter Corporation, Denver, Colorado. Both are providing information on themselves and their companies capabilities.

Other companies to be contacted for a material consultant are the Norton Company, Worcester, Massachusetts, and Coors Porcelain, Golden, Colorado. For the ceramics fabrication other potential consultants are the Bechtel Corporation, Stearns and Foster, and Babcock and Wilcox.

TRW Systems Group requires specific shapes for reflectance and emittance data. It was not possible to provide these shapes out of the existing one inch diameter tubes which are a "self-bonded" silicon carbide. Flat plates of silicon carbide are only made from a "glass-bonded" material. Therefore, property data must be obtained on both types of material. For this reason a three inch diameter silicon carbide tube was ordered to be shipped by air express, to provide sufficient material to machine the required geometrical shape for measurement. After this material was ordered a visit to McDonnel-Douglas Astronautics Company in St. Louis on another program revealed an extensive capability for emittance and reflectance measurements on ceramic material without the geometric constraints imposed by the TRW facility. Also McDonnel-Douglas can make measurements on aluminum oxide to higher temperatures than can TRW. A quotation on the required tests has been requested from McDonnel Douglas.

There will be no problem in modifying the test facility to include an additional tube on either side of the tube under test. Additional silicon carbide tubes were ordered as a precaution against possible breakage, since it will be necessary to place water cooled attachments on the ends of the "dummy" tubes to provide air flow through them. Initial tests will be run with a single tube only prior to modifying the facility by the addition of tubes on either side of the tube under test.

A short proposal is being prepared for additional tests of thermal cycling and pressure testing of joints on full size (4 inch diameter tubes) it is anticipated that this proposal will be completed by November 7, 1975.

Respectfully submitted,

Joe N. Harris
Project Director

jw

A-1757

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

November 26, 1975

Black and Veatch
P. O. Box 8405
Kansas City, Missouri 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 5, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver Open Cycle Gas Turbine Design," For the Period November 1-30, 1975, Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

Radiant Test Facility

As a result of discussions with Mr. Max Akridge of Georgia Tech during the quarterly review meeting held at Black and Veatch on November 14, 1975, the quartz lamp radiant heated test facility has been modified to increase the available heat flux on one inch diameter tubes. The flat array of three quartz lamp modules has been modified by bending the back plate to a modified "C" shape so that the radiant energy from each module converges on a point 6 inches from each module. Due to this modification and the necessity of relocating the entire test facility to a location with sufficient ventilation to remove the excess heat generated by the facility, measurements have not yet been made of the actual heat flux reaching the tubes.

In addition to the above modification the test facility is being upgraded with Georgia Tech funds so that it may be used for high intensity thermal radiation and thermal shock testing. Figure 1 shows the single sided strip concentrator capable of intensities of 550 kW/m^2. Figure 2 shows the quad elliptical concentrator to be used for thermal shock testing and high intensity radiation in a circular pattern. This unit is capable of intensities of 415 kW/m^2. The heat flux available from either unit can be approximately tripled by doubling the rated voltage.

Thermo-Optical Data on Candidate Ceramic Materials

An engineering estimate of $5,100 has been received from McDonnell Douglas to perform similar tests to those outlined for TRW Systems Group at the October 22, 1975 meeting at Black and Veatch. This is not a firm quotation from the McDonnell-Douglas Contract Section. As a result of this estimate the required data can probably be obtained at a lower cost and in a shorter period of time from TRW even though sample preparation to meet the TRW requirements is a more difficult task.

Existing data on the thermophysical properties of aluminum oxide, silicon carbide and cordierite has been collected along with references for sources of each data point. Copies of this data will be forwarded to Black and Veatch and to Dr. John Cummings at EPRI.

Ceramic Fabrication Consultants

Four potential companies who could provide consultants for materials and/or fabrication have been contacted. These are Mine and Smelter Corporation, Denver, Colorado, Foster Wheeler Energy Corporation, Livingston, New Jersey, The Carborundum Company, Niagara Falls, New York, and the Coors Porcelain Company, Golden, Colorado. Literature and suggested personnel to act as consultants have been received from all but Coors Porcelain Company. Companies yet to be contacted are Babcock and Wilcox, Refractories Division, Augusta, Georgia, and the Norton Company, Worcester, Massachusetts. When material is received from these companies all names will be submitted to Black and Veatch along with our recommendation as to which, in our opinion, is best qualified to perform part or all of the tasks required for fabrication. The recommendation may be for two consultants, one for materials and one for fabrication.

Survey of Potential Ceramic Materials for Heat Exchanger Application

As a result of the November 14, 1975 Quarterly Review Meeting, a survey is being conducted of all potential ceramic heat exchanger materials. To date eighteen potential materials have been identified. Thermal, mechanical and optical property data are being compiled for all of these materials, as well as availability, fabricability and cost. It is anticipated that this task will be completed early in December.

Thermal Cyclic Testing

A proposal has been prepared to include construction of a test facility to thermally cycle full-scale (4-inch diameter) heat exchanger tubes. The information is presented here on the construction, test plan and costs to conduct the tests.

Test Facility

The test facility is designed to handle a full-size ceramic "U-tube" with 44 inches of tube length in the radiant heated zone. The inlet and exhaust ends of the ceramic U-tube will be connected to metal headers outside the radiant heated zones. Thus, the U-joint, ceramic joints in the straight section of the tube and the ceramic to metal seals will all be tested simultaneously. Radiant energy will be provided by 84 quartz lamps on each wall of the furnace. These lamp banks are spaced 12 inches apart with the U-tube centered as shown in the cross section of Figure 3. Fused silica foam reflectors are placed on either end of the facility and between the two tubes of the U-tube section. A vertical sectional view is shown in Figure 4. This view shows the metal headers held in place by a castable refractory block to which a vibrator is attached. This source of vibration may be either an electrical 60 cycle vibrator or a lower frequency mechanically driven vibrator. The quartz lamp modules and power supplies are already available in an existing facility. Costs to build the facility will be for the framework, the refractory materials required, the electrical power leads, and the cooling water connections. To supply the air needed will require a 25 to 35 horsepower air compressor. It is anticipated that this will be rental equipment at an estimated cost of $300 per month.

Test Plan

The U-tube will have a joint in each of the straight sections in addition to the U-joints and the ceramic to metal seals at the inlet and exhaust ends of the pipe. Flowing air will be supplied to the tube under test at 120 psig. A temperature sensor will be placed in the air stream of the exhaust header and will be used to activate the quartz lamps. After initial start-up the quartz lamps will remain on until the exhaust air stream reaches 1800° F. At this point the lamps will shut-off until the air stream cools to 500° F. At this point the lamps will come on until the air stream temperature again reaches 1800° F. It is estimated that a complete cycle will be between 15 and 20 minutes and that a complete test will run for 60 days or until failure of some part of the U-tube or ceramic to metal joints. This will mean a test of 5700 to 7200 cycles or more if the cycle time can be shortened without thermal shocking the tubes under test. Tube wall temperature will be monitored by thermocouples at several locations and air pressure and velocity of air flow will be monitored as well as temperature of the air stream. The facility will be so constructed that it will shutdown if cooling water fails, this will include shutoff of electric power and air flow. The system will be automated, however, due to the temperature, high voltages and currents, and air pressures involved a human monitor will be required 24 hours a day.

Time Estimate

It is estimated that construction of the facility will require 6 weeks to 2 months for completion and that a single test of a silicon carbide U-tube section will require 2 additional months. Therefore, the following budget is based on a period of 4 months.

Budget

			4 Months
Personal Services			$19,235
Principal Research Engineer	½ man month	$1,150	
Senior Research Engineers	3 man months	5,620	
Research Engineers	3 man months	4,200	
Technicians	6½ man months	6,825	
Machinists	1 man month	1,050	
Miscellaneous Personnel	½ man month	390	
Materials and Supplies:			18,000
Electrical Wire	$2,400		
Refractories & other Furnace Matls.	3,000		
SiC Test Sections (2 sets)	4,000		
Other Control Modifications & Equipment	5,000		
Compressor Rental 3 months	900		
Electrical Power	2,700		
Staff Benefits at 8.936 percent of Personal Services			1,719
Overhead at 68 percent of Personal Services			13,080
		Total	$52,034

Of the above budget it is estimated that $18,300 is for construction of the facility. This leaves a cost of $33,734 for the test which includes $4,000 for the "custom made" U-tubes.

It is estimated that the radiant test facility could be operated with only 84 quartz lamps mounted on one side with a ceramic reflecting surface opposite. This would reduce the cost of electrical wire for hooking up the test facility by halving the current load and would likewise decrease the electrical power bill by one-half. However, the tubes would be more subject to thermal shock from asymmetric heating and the cycle time would have to be lengthened.

If this proposal is satisfactory we will be pleased to submit a formal proposal in greater detail as to facility, construction and test plan.

Respectfully submitted,

Joe N. Harris
Project Director

jw

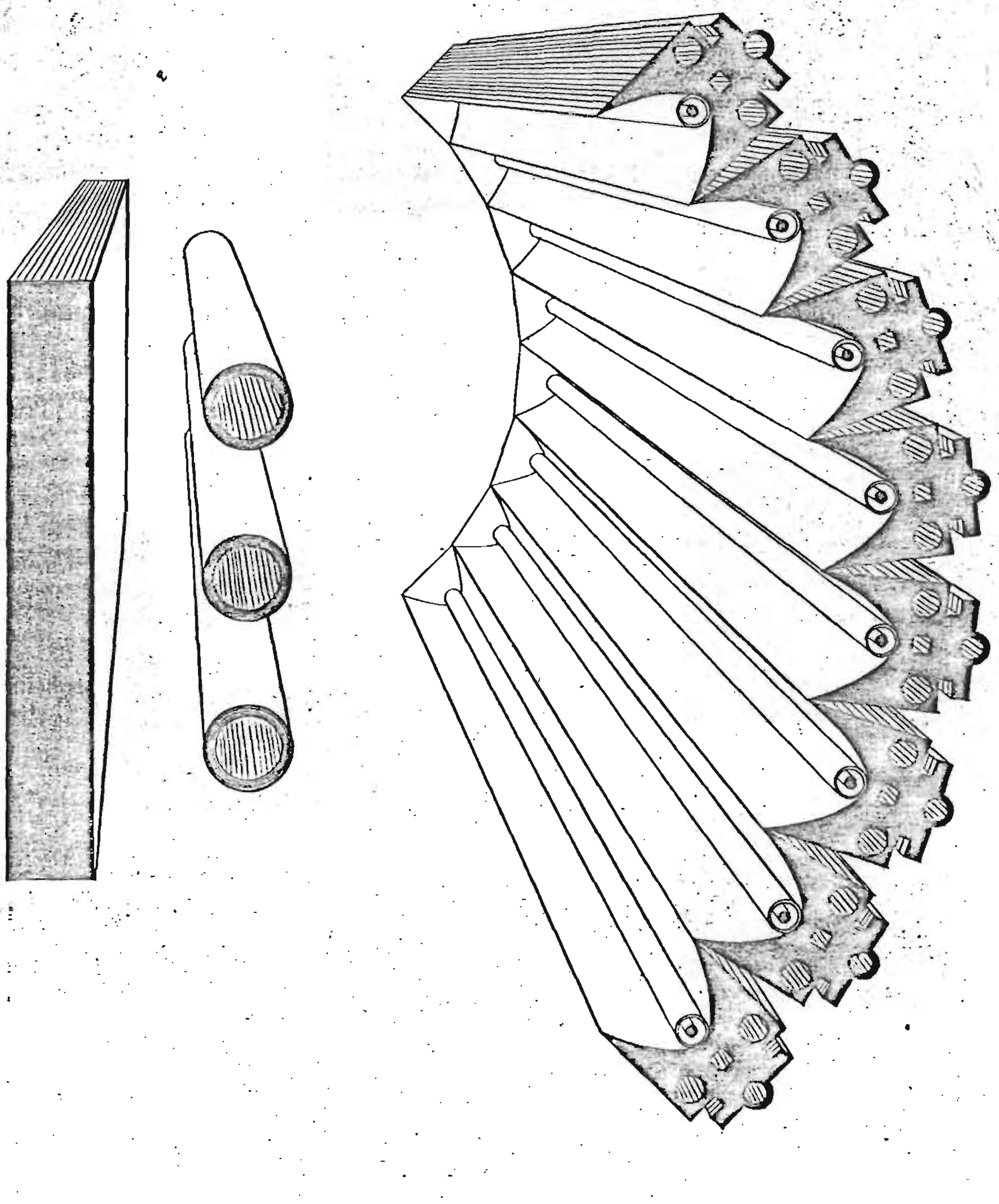


Figure 1. Single Sided Strip Concentrator Array.

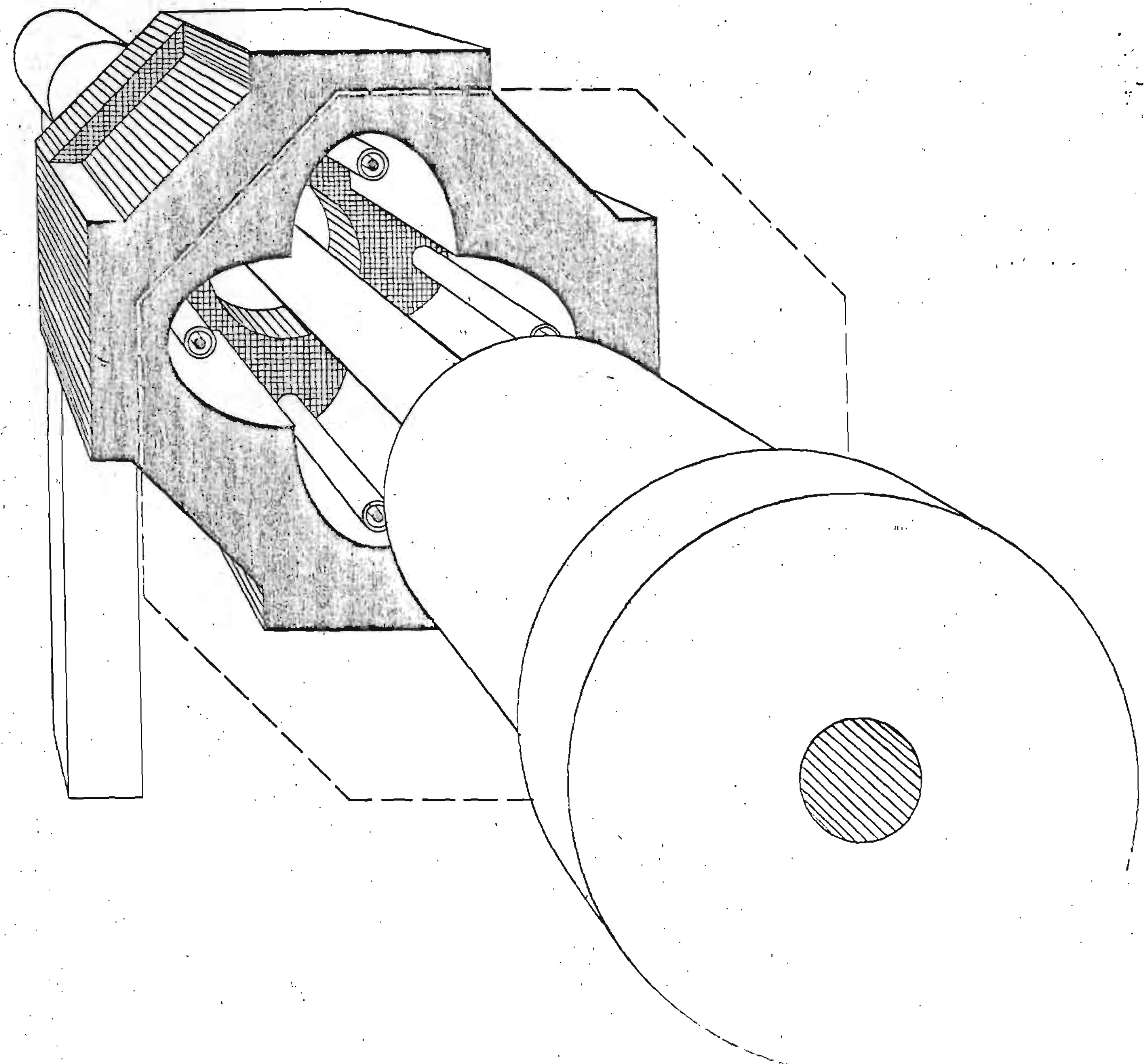


Figure 2. Quad Elliptical Concentrator for Thermal Shock Testing.

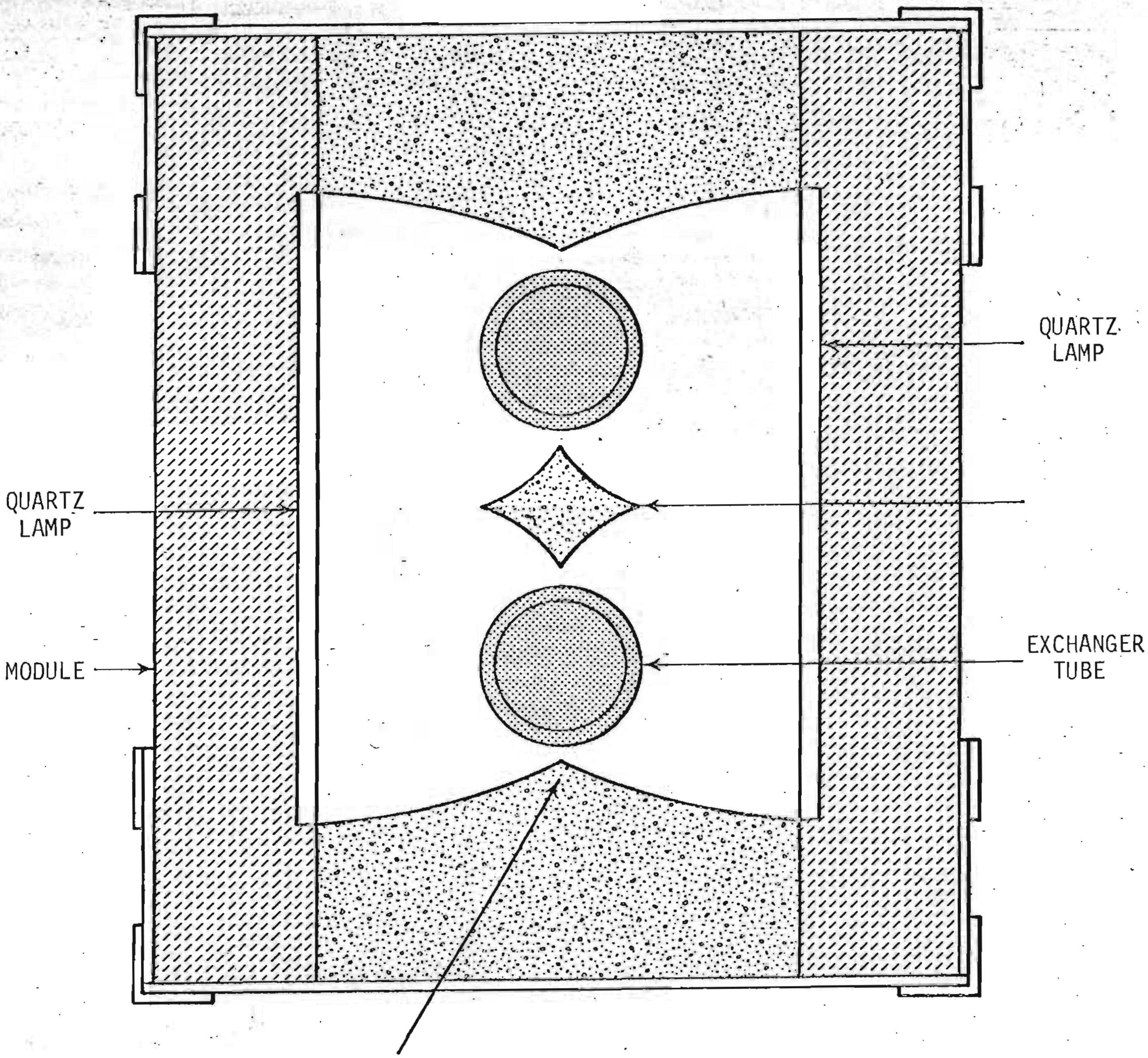


Figure 3. Horizontal Cross-Section of Radiant Cyclic Test Facility.

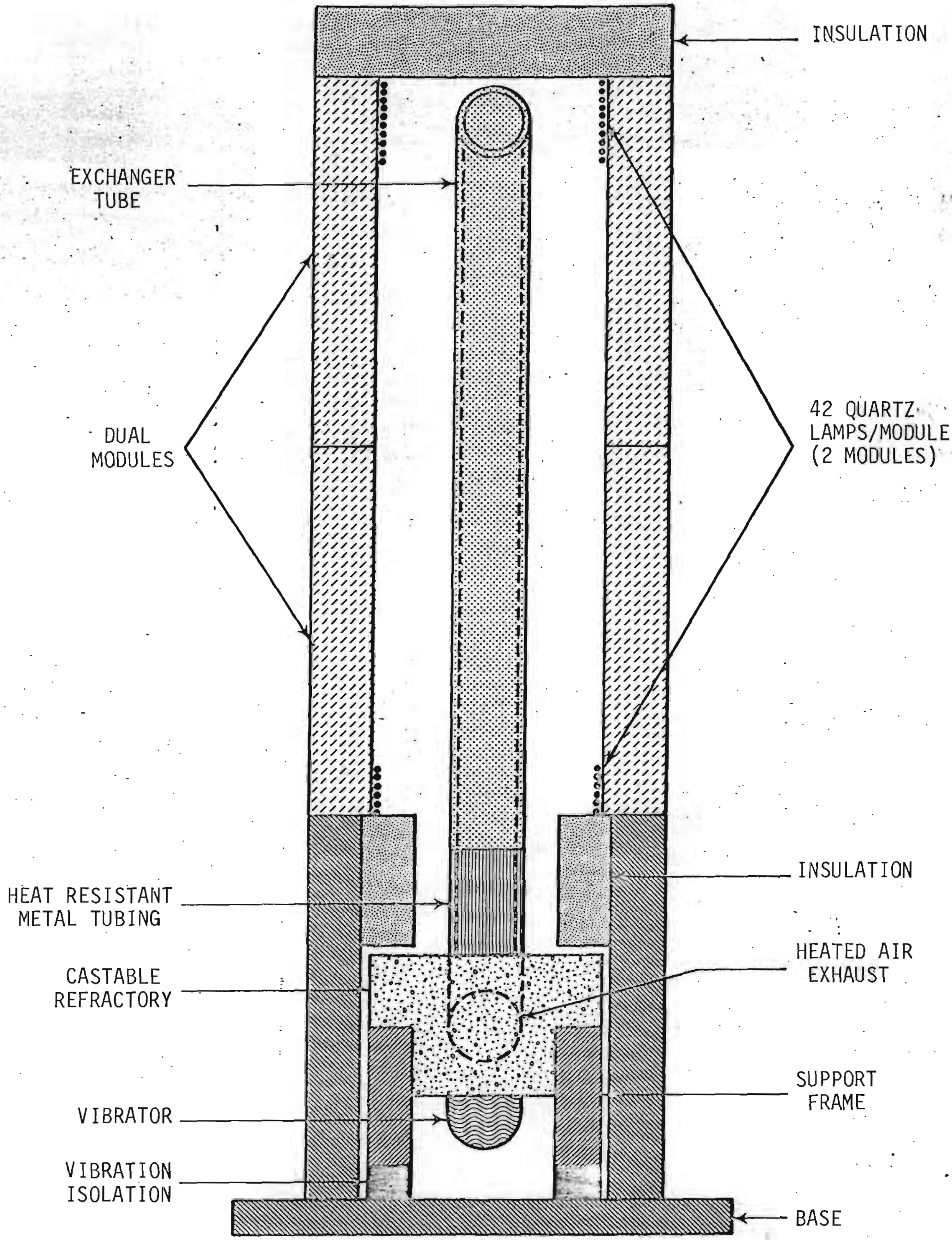


Figure 4. Vertical Cross-Section of Radiant Cyclic Test Facility.

A 1757

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

January 8, 1976

Black and Veatch
P. O. Box 8405
Kansas City, Missouri 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 6, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design" for the Period December 1-31, 1975, Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

Radiant Test Facility

a. Flux Measurements

The quartz lamp array providing infrared radiant heating is currently arranged in a modified "C" shape. The array consists of three quartz lamp modules. Each module has 6 quartz lamps rated at 1.6 kilowatts each and an effective heating length of 16 inches. The two outside modules are inclined 31 degrees so that the radiant energy from each module converges on a single line 6 inches from each module.

The radiant flux was determined at the position of the tube under test (without the tube in place) using a Hy Cal Engineering Model C-1300-A-160-072 Asymptotic water cooled calorimeter. Flux levels were measured at the tube position in the center of the array and at a position 1½ inches from the end of the heated areas of the lamps. Measurements were made in one inch increments at distances of 2 to 6 inches from the lamp surface and at lamp voltages of 250 and 280. Measurements were also made with only the center module lighted (flat array).

Measurements were made without the silicon carbide tubes in place and without the silicon carbide reflector plate. Flux level measured at each position and under the conditions specified are given in Table I.

b. Heat Transfer Measurements

Initial data were taken to become familiar with the test facility operation and to correct defects in the test set-up. Initially low flow rates were used because of a malfunction in the air preheater which precluded a high input temperature to the tube test section. Low air pressures were used on the initial tests to be certain that there were no compression failures on the tube or silica butt joints, however, the system has now been tested at 120 psig without tube or holder failure. Future tests will be made at 120 psig. The compressor currently being used cannot maintain a flow of 18 cfm required to give an input (room temperature) velocity of 100 ft/sec. However, the addition of an air line from a second compressor should now allow sustained flow rates with input velocities up to 200 ft/sec. Preliminary test data on heat transfer under various conditions are given in Table II.

Thermo-Optical Data on Candidate Ceramic Materials

TRW Systems Group has received the Georgia Tech Purchase Order for the following measurements:

a. Total hemispherical emittance of silicon carbide at 1000^{o}, 1300^{o}, 1600^{o}, 1900^{o}, 2200^{o} and 2500^{o} F.

b. Spectral reflectance of silicon carbide at 1370^{o} K

c. Room temperature spectral reflectance of silicon carbide at polar angles of 15^{o}, 30^{o}, 45^{o}, 60^{o} and 75^{o}.

d. Room temperature spectral reflectance measurements on cordierite at polar angles of 15^{o}, 30^{o}, 45^{o}, 60^{o} and 75^{o}.

e. Directional emittance of cordierite to 1370^{o} K. Data will be used to calculate total hemispherical measurements.

The necessary specimens of KT silicon carbide (Carborundum) have been machined from a 3-inch outside diameter, ¼-inch wall tube. These are now being thermally aged prior to shipment to TRW. The cordierite specimens have been ordered from Coors Porcelain Company and receipt is expected in the month of January.

Survey of Potential Ceramic Materials for Heat Exchanger Applications

Table III lists property data obtained in a survey of potential ceramic materials for heat exchanger applications. This survey is not complete, but data obtained thus far is presented here.

Visit

Drs. J. C. Grosskreutz and E. J. McBride were at Georgia Tech on December 30, 1975, to discuss the program, to see the radiant test facility in operation, and to discuss changes in the statement of work for the thermal cyclic test facility for testing of ceramic "U" tubes.

Ceramic Fabrication Consultants

Data are still being received by mail from potential consultants for both the ceramic components and for full facility fabrication. A full analysis and justification company by company and a final recommendation from Georgia Tech must await receipt of all data. However, with the data currently available we believe the best ceramic material consultant to be Hague International and the facility fabricator to be Foster-Wheeler. The material consultant could change to Coors if cordierite is the material of choice. The facility fabricator recommendation could change to Babcock and Wilcox or the Garret Corporation pending receipt of their capabilities.

Thermal Cyclic Testing

The thermal cyclic testing work statement is currently being revised and should be submitted to Black and Veatch next week. Discussions with Mr. Paul LeHaye of Hague International on January 5, 1976 make the idea of a metal "U" above the radiantly heated zone appear to offer the best solution for testing the "U" tube concept at this time. Mr. LeHaye will submit a bid on fabricating the U tubes and one inch diameter tubes 16 inches in length for the current test facility.

Work for the Next Report Period

The current configuration of quartz lamps will be thoroughly mapped for flux density as discussed with Drs. Grosskreutz and McBride during their visit to Georgia Tech. Flux will be measured with the HyCal Engineering Calorimeter with the reflector in place by cutting holes in the reflector to accommodate the calorimeter. Flux will be measured at the center and near each end at the position of the upper tube the center (test) tube and half-way between the tubes for various distances from the lamps.

The same information will be obtained with the quartz lamp modules in a flat array

Heat transfer data will be obtained on a silicon carbide tube with flowing air through the tube at 120 psig. The tube will be instrumented with six thermocouples placed 60 degrees apart around the circumference of the tube, at the center of the tube. It is anticipated that these thermocouples will be held in contact with the tube by drilling shallow holes in the surface of the tube and peening the thermocouples in place. Silicon carbide tubes will be placed approximately one diameter above and below the test tube and a silicon carbide reflector placed behind the tubes (opposite the quartz lamp array). The same information will be obtained on the Coor's cordierite tubes when received.

Georgia Tech's recommendations for consultant(s) will be submitted to Black and Veatch with justification for the choice. Information will be submitted on all candidate consultants in order of preference.

Data will be obtained from TRW on the thermo optical properties of silicon carbide and cordierite materials submitted to them.

The work statement for the thermal cyclic testing of ceramic "U" tubes will be revised and submitted through Black and Veatch to the Electrical Power Research Institute.

Respectfully submitted

Joe N. Harris
Project Director

jw

TABLE I

FLUX LEVELS PRODUCED BY QUARTZ LAMP ARRAY

Sensor Centered

Distance (inch)	Lamp Voltage (volts)	Flux Level (kw/m^2)	Remarks
6	250	114	
6	280	136	
6	250	44	center bank only
5	250	126	
5	280	150	
5	250	53	center bank only
4	250	142	
4	280	170	
4	250	65	center bank only
3	250	151	
3	280	181	
3	250	84	center bank only
2	250	159	
2	280	191	
2	250	116	center bank only

Sensor 1½ Inches from End of Tube

Distance (inch)	Lamp Voltage (volts)	Flux Level (kw/m^2)	Remarks
6	250	85	
6	280	102	
6	250	32	center bank only
4	250	119	
4	280	142	
4	250	54	center bank only
2	250	148	
2	280	181	
2	250	111	center bank only

TABLE II

PRELIMINARY DATA FOR HEAT TRANSFER TO AIR FLOWING THROUGH A RADIANTLY HEATED SiC TUBE

Pressure (psig)	Flow Rate (cfm)	Input Temp (^oF)	Temp Rise (^oF)	Reflector	Notes
3	12	∿ 120	376	SiO_2	1,2,3,6
4	20	∿ 120	308	SiO_2	1,2,3,6
20	12	∿ 120	343	SiO_2	1,2,3,6
30	11	∿ 120	357	SiO_2	1,2,3,6
50	8	129	234	SiO_2	1,2,3,6
50	8	176	244	SiC	1,2,3,6
50	8	129	154	none	1,2,3,6
4	11	1160	130	SiO_2	3,4,5,6
4	11	1200	39	none	3,4,5,6

NOTES:
1. Lamps 6" from tube wall in array bent 31^o.
2. Lamp voltage approximately 250 volts.
3. Flow rates approximate.
4. Lamps 3" from tube wall in array bent 31^o.
5. Lamp voltage 280 volts.
6. Dummy tube not in place.

Property \ Material	Silicon Carbide (KT-SiC)	Reference	Aluminum Oxide (Al_2O_3)	Reference	Cordierite ($MgO \cdot Al_2O_3 \cdot SiO_2$)	Reference	Silicon Nitride (Si_3N_4)	Reference	Boron Nitride (BN) (II)	Reference	Graphite (C)	Reference
Density (gm/cc)	3.10	1	3.98	9	2.51	3	3.2	7	2.3	7	2.22	11
Porosity (%)	0	1	2.0	9	0.03	3						
Maximum Working Temperature ($^oF \times 10^2$)												
Inert Atmosphere	42	1	35	9					55	2	54.3	2
Oxidizing Atmosphere	30	1	35	9					25.5	2		
Flexural Strength (psi x 10^3)												
@ 70° F	27	2	30	9	12.2	3	19.6	9	15.5	2	4	13
@ 2000° F	22	1	20	9			26	9	2.2	2	5	13
Tensile Strength (psi x 10^3)												
@ 70° F			37	10	15.9	9	15.9	7			2.2	13
@ 2000° F			33	10					0.4	2	2.5	13
Compressive Strength (psi x 10^3)												
@ 70° F	150	1	150	9	33.6	3	75	9	45	2	4.9	13
@ 2000° F			50	9							6	13
Elastic Modulus (psi x 10^6)												
@ 70° F	56	1	57	10			3.0	9	12.46	2	1.65	13
@ 1000° F	54	2	54	10			8.0	9			1.70	13
@ 2000° F	51	1	48	10			8.0	9	1.65	2		
Thermal Conductivity (Btu/in/hr.ft² °F)												
@ 500° F mean			111	10					106	2		
@ 1000° F mean	720	1,12	70	10								
@ 1500° F mean	465	1,12	53	10								
@ 2000° F mean	250	1,12	44	10					86	2		
Mean Specific Heat (70°-2000° F)	0.34	1,12	0.25	9,10,15			0.25	9	0.03	12		
Coefficient Thermal of Expansion (in/in°F x 10^{-6})												
70° F-500° F	3.6	17	3.85	10	1.6	12	4.1	16				
70° F-1000° F	3.7	1,2,17	4.16	10	2.0	12	4.8	16				
70° F-1500° F	3.7	17	4.49	10	2.4	12	4.8	16				
70° F-2000° F	3.8	17	4.58	10	2.8	12	6.2	16	0.42	2		
Total Emittance												
500° F	0.65	4	0.77	12,14	0.39	3						
1000° F	0.70	4	0.62	12,14	0.77	3						
1500° F	0.79	2	0.49	12,14	1.02	3						
2000° F	0.86	2	0.46	14	1.24	3						
Spectral Emittance												
70° F	0.18	14	0.89	14								
2000° F	0.71	14	0.33	14								

Property \ Material	Hafnium Diboride (HfB_2)	Reference	Zirconium Diboride (ZrB_2)	Reference	Zirconium Carbide (ZrC)	Reference	Zirconium Oxide (ZrO_2)	Reference	Tungsten Carbide (WC)	Reference	Titanium Carbide (TiC)	Reference
Density (gm/cc)	11.20		6.10	7	6.80	9	5.61	2	15.6	2	4.92	7,9
Porosity (%)												
Maximum Working Temperature ($^oF \times 10^2$)												
Inert Atmosphere							40	2	36.3	2	27	9
Oxidizing Atmosphere					18	9	43.5	2	12.9	2	14.7	9
Flexural Strength (psi x 10^3)												
@ 70° F			29	7	30	7	26	9	84	2,9	124	7
@ 2000° F					20	9			70	9	50	9
Tensile Strength (psi x 10^3)												
@ 70° F					23	7	20	9	50	2,9	68	7
@ 2000° F					12	9	13	9			40	9
Compressive Strength (psi x 10^3)												
@ 70° F			29	7	238	7	300	9			190	7,9
@ 2000° F							150	9				
Elastic Modulus (psi x 10^6)												
@ 70° F	37	7	50	7	69	7	25	9	78	2	45	7,9
@ 1000° F							23	9				
@ 2000° F												
Thermal Conductivity (Btu/in/hr.ft² °F)												
@ 500° F mean												
@ 1000° F mean												
@ 1500° F mean												
@ 2000° F mean												
Mean Specific Heat (70°-2000° F)												
Coefficient Thermal of Expansion (in/in°F x 10^{-6})												
70° F-500° F												
70° F-1000° F												
70° F-1500° F												
70° F-2000° F												
Total Emittance												
500° F												
1000° F												
1500° F												
2000° F												
Spectral Emittance												
70° F												
2000° F												

Property \ Material	Titanium Nitride (TiN)	Reference	Molybdenum Disilicide ($MoSi_2$)	Reference	Fused Quartz (SiO_2)	Reference	Pyroceram 9606	Reference	Mullite $3 Al_2O_3 \cdot 2 SiO_2$	Reference	Beryllium Oxide BeO	Reference
Density (gm/cc)	5.43	9	6.24	7	2.24		2.6	15	3.16	7	3.01	7
Porosity (%)					0						1.00	7
Maximum Working Temperature ($^oF \times 10^2$)												
Inert Atmosphere	40	9			18						32.7	9
Oxidizing Atmosphere	20	9			18						36	9
Flexural Strength (psi x 10^3)												
@ 70° F	34	7,9	50	7,9			38	15			40	7,8
@ 2000° F			26	7			7	15			13	8
Tensile Strength (psi x 10^3)												
@ 70° F	-		22	7			22	15			15	9
@ 2000° F			43	7			5.5	15			10	9
Compressive Strength (psi x 10^3)												
@ 70° F	185	7,9									200	9
@ 2000° F											50	9
Elastic Modulus (psi x 10^6)												
@ 70° F	36	9	53	7			17.2	15			56	7,9
@ 1000° F												
@ 2000° F												
Thermal Conductivity (Btu/in/hr.ft² °F)												
@ 500° F mean												
@ 1000° F mean												
@ 1500° F mean												
@ 2000° F mean												
Mean Specific Heat (70°-2000° F)												
Coefficient Thermal of Expansion (in/in°F x 10^{-6})												
70° F-500° F												
70° F-1000° F												
70° F-1500° F												
70° F-2000° F												
Total Emittance												
500° F												
1000° F												
1500° F												
2000° F												
Spectral Emittance												
70° F												
2000° F												

TABLE III (Continued)

THERMOPHYSICAL PROPERTIES OF
SELECTED REFRACTORY MATERIALS

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A 1757

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

February 5, 1976

Black and Veatch
P. O. Box 8405
Kansas City, Missouri 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 7, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design," for the Period January 1-3, 1976, Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

Radiant Test Facility

a. Heat Transfer Measurements

Data were obtained under many different conditions of temperature and pressure on silicon carbide tubes. Data were taken with and without a reflecting surface behind the tubes. Initially a silicon carbide reflector was used, but this was later changed to a fused silica foam reflector because the fused silica reflector produced a more even temperature distribution around the tube. "Dummy" tubes were placed on either side of the tube under test. Initially these tubes were not cooled. However, due to concern that these "dummy" tubes would become hotter and radiate more energy to the tube under test it was decided to cool the dummy tubes, with unrestricted flowing air, to a surface temperature approximating the surface temperature of the tube under test. Air was supplied to the two dummy tubes from a separate air supply and was fed to the tubes through a "Y" with the assumption that both tubes were receiving the same volume of air.

A thermocouple was placed on the upper dummy tube at a point on the circumference closest to the surface of the tube under test. (Thermocouple 8 in Figure 1.) During operation of the quartz lamps the air flow through the dummy tubes was adjusted until the thermocouple on the dummy tube (8) was reading as close as possible to the value of thermocouple 5 on the tube.

The limiting factors on the test are preheater temperature capability, and continuous air flow at high pressures. The system was initially designed for 60 psi operation with air velocities through the tube of 100 feet per second. Some increase in air flow was attained by manifolding two air compressors.

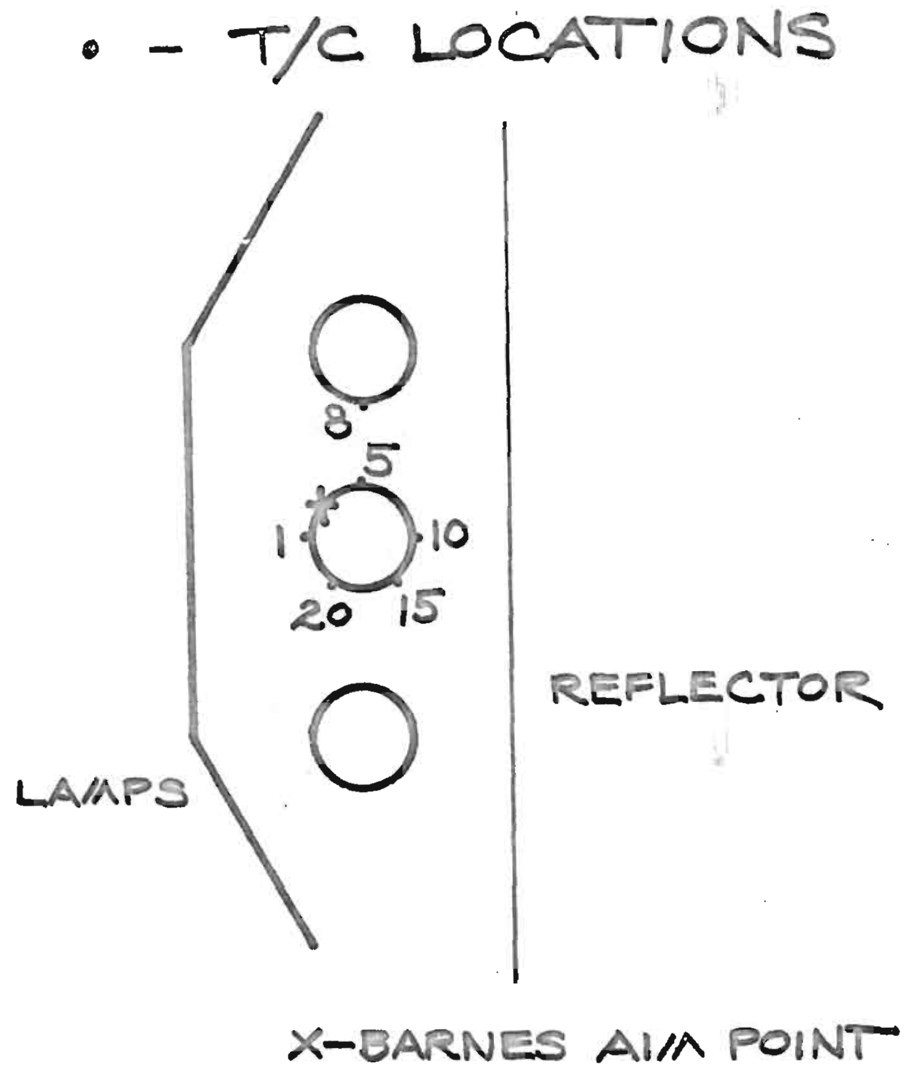


Figure 1. Diagram of Tube Surface Thermocouple (T/C) Locations.

This gave operational capacity up to 100 psig with a sustained cold air flow of 12.3 cfm. Flowing air at this pressure limited the preheater output to 500° F air. Maximum output of the preheater was 1500° F air at 100 psig when the flow of cold air was reduced to 3 cfm.

A second preheater was constructed, but has not been put into service because all attempts to locate a second copper tube of sufficient diameter to form the water cooled shell have been unsuccessful. A stainless steel water cooled shell is being considered for the second preheater if it can be attained within the funds of the current contract. Data obtained thus far on silicon carbide tubes are given in Table I.

b. Flux Measurements

A mapping of the flux reaching the silicon carbide tubes under test and the flux on the fused silica reflector was initiated with the quartz lamps in the modified C-array. Data were obtained using a Hy Cal Engineering Model C-1300-A-160-072 Asymptotic water cooled calorimeter. All flux measurements were made with the fused silica reflector in place. To provide for the calorimeter electrical and water cooling leads one inch diameter holes were drilled in the fused silica reflector at the positions shown in Figure 2. All positions except the one in use for the calorimeter were closed with fused silica plugs during actual flux measurements. The sensor portion of the one inch diameter calorimeter is approximately 1/8 inch in diameter and for each test position was located as shown in Figure 2. Measurements were intended to be made at the front surface of each tube (i.e., tangent to the silicon carbide tubes at their closest position to the quartz tubes). However, the calorimeter could not be placed closer than the centerline of the silicon carbide tubes with the array in the modified-C position without setting fire to the electrical leads. The tube and reflector spacings are:

1. Distance from active tube centerline to front surface of quartz lamps, 3 inches.

2. Distance from dummy tubes centerline to front surface of quartz lamps, 2½ inches.

3. Distance from active tube to dummy tubes centerline to centerline, 2½ inches.

4. Distance from tube centerlines to reflector surface, 1-3/4 inches.

5. Sensor positions 1, 3 and 5 are centered on the quartz lamps (8 inches from either end).

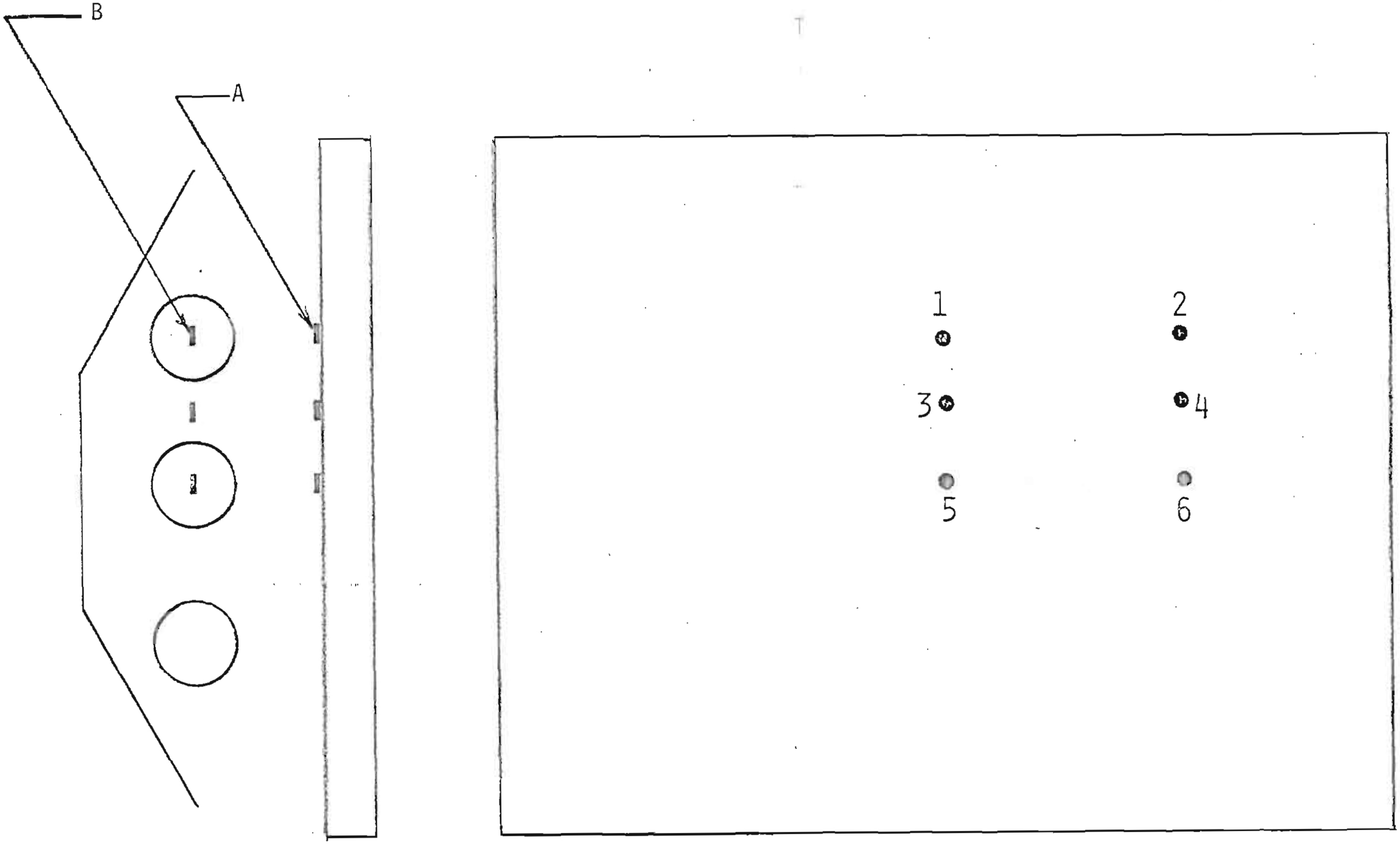
TABLE I

HEAT TRANSFER DATA FOR SILICON CARBIDE TUBE

Pressure in Tube (psig)	Preheater Output (°F)	Flow Cold (cfm)	Barnes IR Pyrometer	Tube Surface Temperatures (°F) T/C 1	T/C 5	T/C 10	T/C 15	T/C 20	T/C 8	Δ T Across Tube (°F)	Notes
100	1500	3	---	1783	1794	1703	1737	1703	1681	70	1,5,4
60	500	18	1250	1525	1350	1318	1307	1415	1591	240	1,5,4
100	520	12.3	1250	1576	1426	1389	1381	1487	---	248	1,5
60	500	19.7	1300	1490	1340	1312	1303	1402	---	254	1,5
30	500	18.7	1450	1616	1514	1481	1472	1569	---	331	1,5
15	500	18.7	1550	1701	1634	1591	1580	1678	---	391	1,5
0	500	21	1810	1760	1715	1672	1625	1751	---	427	1,5
0	500	21	1750	1794	1731	1674	1674	1720	---	418	1,6
60	500	19	1475	1822	---	1650	---	1632	---	252	1,7
30	500	19	1600	---	---	---	---	---	---	337	1,7
15	500	19	1725	---	---	---	---	---	---	394	1,7
0	500	21	1825	---	---	---	---	---	---	464	1,7
0	500	45	1650	---	---	---	---	---	---	338	1,7
30	1250	6.2	---	1703	---	1285	---	1479	---	100	1,7,8
30	820	25	---	1567	---	1201	---	1348	---	194	1,7,8
30	1380	6.2	---	1820	---	1705	---	1705	---	143	1,7,8
4	1160	29	---	---	---	---	---	---	---	130	2,8
4	1200	29	---	---	---	---	---	---	---	39	2,8,9
50	176	11	---	---	---	---	---	---	---	155	3,8,10

Notes:
1. Lamp voltage 280, lamps bent 31° three inches from tube wall, dummy tubes in place.
2. Lamp voltage 280, lamps bent 31° three inches from tube wall, no dummy tubes in place.
3. Lamp voltage 280, lamps bent 31° six inches from tube wall, no dummy tubes in place.
4. Dummy tubes air cooled.
5. T/C's under white cement module and peened into small holes in SiC tube.
6. T/C's not under cement and peened into SiC tube.
7. T/C's pulled into poor contact with SiC tube not cemented or peened.
8. Pressure in tube possibly inaccurate due to pressure drop in constricted line.
9. No reflector.
10. SiC reflector.
11. If no Note 9 or 10 then reflector was fused silica foam.

CALORIMETER POSITIONS



●, ▮ - SENSOR

A = Sensor surface flush with inside surface of reflector, all tubes in place.

B = Sensor surface approximately as shown, top tube removed for positions 1 and 2, center tube removed for positions 5 and 6.

Figure 2. Diagram of Heat Flux Sensor Locations.

6. Sensor positions 2, 4 and 6 are 1½ inches from the active end of the quartz lamps.

Heat flux measurements were made at the six reflector positions with the quartz lamps operating at 280 volts and with air (800° F, not pressurized) flowing at 12 cfm (input to the preheater) through the active tube. Room temperature air was flowing through the dummy tubes at a rate to bring the temperature recorded by thermocouple 8 as close as possible to the temperature indicated by thermocouple 5 (Figure 1). Data obtained for these six reflector surface positions are given in Table II.

Flux measurements at the upper dummy tube position and at the active tube position were made with those respective tubes removed. Flux measurements at the mid-points between the two tubes were made with the silicon carbide tubes in position and with air flowing. These data are also given in Table II.

Thermo-Optical Data on Silicon Carbide

TRW Systems Group has received the required Carborundum "KT" silicon carbide samples prepared and thermally aged at Georgia Tech. Spectral data has been promised to be reported telephonically not later than February 13, 1976. Total hemispherical emittance data will require a longer period for completion and no estimated date has been given by TRW.

Visits to Potential Ceramic Heat Exchanger Tube Suppliers

a. Coors Porcelain

On Wednesday, January 21, 1976, Mr. J. N. Harris of Georgia Tech met with personnel of Black and Veatch and Coors Porcelain Company at Golden, Colorado to discuss the potential use of Coor's cordierite tubes in a solar air heat exchanger. The properties of the material and potential methods of forming ceramic to ceramic, and ceramic to metal joints were discussed. Also discussed was the feasibility of forming U joints.

Coors has provided us with a verbal quotation of $2,489 to provide two, 48-inch long by 2-inch outside diameter, by 1/8-inch wall cordierite U tubes unassembled with sleeves for joining the U and sleeves in the two straight sections. They have also provided a quote of $280 for providing 8 sleeves for joining one inch outside diameter tubes for testing smaller joints.

Mr. Wendall Brown of Coors Porcelain has achieved promising results in bonding the cordierite tubes with Saureisen No. 8 cement. The joint showed good shear strength after thermally cycling to 1200° C.

TABLE II

FLUX MEASUREMENTS

Center Tube Flow In (cfm)	Center Tube Flow Out (cfm)	Calorimeter Position	Flux Level (Btu/ft^2-sec)	Flux Level (kw/m^2)	Tube Surface Temp (°F) T/C 1	T/C 5	T/C 10	T/C 20	T/C 8	Barnes Pyrometer (°F)	Preheater Out (°F)
12	12	1A	12.8	145	1795	1795	1705	1830	1820	1725	810
12	12	2A	10.9	124	1795	1795	1705	1830	1820	1725	810
12	12	3A	12.0	136	1795	1795	1705	1830	1820	1725	810
12	12	4A	10.4	118	1795	1795	1705	1830	1820	1725	810
12	12	5A	11.8	134	1795	1795	1705	1830	1820	1725	810
12	12	6A	9.7	110	1795	1795	1705	1830	1820	1725	810
12	12	1B	20.4	232	1890	1795	1705	1850	---	1625	810
12	12	2B	17.3	196	1890	1795	1705	1850	---	1625	800
12	12	3B	16.8	191	1785	1805	1705	1840	1820	1700	800
12	12	4B	9.7	110	1785	1805	1705	1840	1820	1700	800
---	---	5B	18.6	211	---	---	---	---	1820	1125[1]	---
---	---	6B	15.1	171	---	---	---	---	1820	1125[1]	---

[1] Barnes pyrometer aimed at reflector.

b. The Carborundum Company

On Friday, January 23, 1976, Mr. Max Akridge of Georgia Tech met with personnel of Black and Veatch and the Carborundum Company to discuss the potential use of silicon carbide "U" tubes in a solar air heat exchanger and to discuss the problems of joining the silicon carbide. A copy of Mr. Akridge's trip report has previously been provided to Black and Veatch.

A bid for four KT silicon carbide tubes, 2 inch outside diameter by 48 inch length with a brazed joint midway has not been received and attempts to reach Dr. Coppola at Carborundum by telephone have been unsuccessful.

c. Hague International

A written bid has been received from Hague International for their "CERHX" material. The price quoted for three 16-inch long tubes one inch OD x 1/8 inch wall and one tube with the same dimensions, but with a joint in the center is $9,200. The price quoted for two 48-inch "U" tubes with joints in each leg is $20,300.

Ceramic Fabrication Consultants

The naming of a suggested fabrication consultant is again delayed pending a selection of ceramic material.

Work for the Next Report Period

Mapping of the flux distribution in the modified C-shape and with a flat panel array will be completed. Heat transfer data on the cordierite tubes from Coors Porcelain will be completed if they are received in time. Currently it is anticipated that they will be received during the second week of February. Additional data on the silicon carbide tubes will be obtained with higher air input temperatures by using two preheaters. The current set-up will be limited to 100 psig air.

The cordierite thermo optical properties samples will be submitted to TRW after receipt and thermal aging.

Respectfully submitted,

Joe N. Harris
Project Director

jw

A-1757

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

March 15, 1976

Black and Veatch
P. O. Box 8405
Kansas City, Missouri 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 8, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design," for the period February 1-29, 1976, Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

Additional tests were run on silicon carbide tubes to provide data under operating conditions not previously investigated. These data were taken using a different SiC tube than had been used previously due to breakage of the tube during installation of a new thermocouple. The tube used was identical in size and manufacture to the previously tested tube. In addition to two new data points, data were obtained at three previously investigated points to check repeatability of the data from tube to tube. These data are summarized in Table 1.

Cordierite tubes were installed in the test set up in the same manner as the SiC tubes. Five thermocouples were placed on the "active" tube surface and one on the top "dummy" tube by cementing the thermocouple bead into a shallow dimple in the tube surface. No "peening" of the thermocouple was attempted because of the danger of breakage of the cordierite tubes. Tube location and numbering of the thermocouples were the same as on the SiC tubes. The "dummy" tubes were air-cooled and the deflector was fused silica foam. The surface temperature of the air cooled "dummy" tube was more difficult to control than with the SiC tubes, but was held as close to the surface temperature of the "active" tube as possible. Pressure, flow rate, and preheater output temperatures were selected to duplicate the conditions under which the SiC tubes were tested. The data are summarized in Table 2.

Respectfully submitted,

Joe N. Harris
Project Director

jw

TABLE I

ADDITIONAL HEAT TRANSFER DATA FOR SILICON CARBIDE TUBES

Pressure in Tube (psig)	Preheater Output (^{o}F)	Air Flow (cfm)	Tube Surface Temperature (^{o}F): Barnes IR Pyrometer (^{o}F)	T/C 1	T/C 5	T/C 10	T/C 15	T/C 20	T/C 8	ΔT Across Tube (^{o}F)
60	500	12	1375	1615	1560	1460	1415	1505	1590	250
60	500	8	1450	1660	1590	1525	1460	1525	1590	275
15	500	19	1425	1545	1615	1540	1445	1505	1635	274
30	500	19	1375	1615	1545	1460	1385	1460	1615	240
0	500	21	1550	1710	1658	1590	1480	1525	1620	330

Note: Conditions same as previous SiC test data.

TABLE II

HEAT TRANSFER DATA FOR CORDIERITE TUBES

Pressure in Tube (psig)	Preheater Output (^{o}F)	Air Flow (cfm)	Tube Surface Temperature (^{o}F): Barnes IR Pyrometer (^{o}F)	T/C 1	T/C 5	T/C 10	T/C 15	T/C 20	T/C 8	ΔT Across Tube (^{o}F)
0	500	17	1500	1658	1647	1818	1525	1636	1580	265
15	500	18	1350	1536	1536	1394	1426	1503	1525	202
30	500	18	1150	1437	1394	1286	1340	1459	1415	153
60	425	18	1000	1329	1318	1148	1222	1372	1297	115
60	500	12	1100	1437	1361	1244	1308	1481	1351	242
60	500	8.3	1150	1503	1448	1329	1372	1525	1308	176
100	480	8.0	1000	1276	1201	1179	1254	1426	1244	124
100	500	3.6	1150	1437	1361	1361	1405	1514	1276	242
0	800	7.9	1750	1760	1715	1569	1591	1738	1591	306
15	800	8.0	1650	1715	1681	1525	1558	1715	1591	244
30	800	8.1	1625	1681	1636	1481	1525	1681	1569	185

Notes:
1. Lamp voltage 280, lamps in modified "C" array three inches from cordierite tube wall.
2. Dummy tubes in place and air cooled.
3. Fused silica reflector.
4. T/C's inserted into shallow dimple in tube surface and cemented in place with white cement module.
5. Flow rates are actual cfm at 74^{o} F.

A-1757

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

April 7, 1976

Black and Veatch
P. O. Box 8405
Kansas City, Missouri 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 9, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design," for the period March 1-31, 1976, Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

The two candidate ceramic materials, silicon carbide and cordierite, have several disadvantages for fabricating into a large heat exchanger. Some of these disadvantages are:

a. Silicon Carbide

(1) cost

(2) joining requires specialized techniques, personnel and equipment not readily available in the areas in which the central receivers are expected to be located.

(3) the technology for forming a "u" or "hairpin" bend is not yet developed.

b. Cordierite

(1) availability - process is still in pilot plant stage at Coors Porcelain

(2) there is no proven joining technique.

Even with the stated disadvantages these two materials are still the best available candidates. Fused silica has definite advantages over silicon carbide and cordierite in fabrication technology and cost. It has not previously been considered because:

a. it was felt that reflections would result in too much energy loss.

b. it was felt that devitrification might occur due to the operating temperature of the tubes. If this happened tubes would fail in thermal stress.

Silica occurs in approximately two dozen different modifications, but for our applications those of interest are fused silica and cristobalite. Fused silica is amorphous on a macroscopic scale and is formed by reasonably rapid cooling of melts of any of the crystalline forms. Cristobalite is a tetragonal crystalline form, which is the usual product of the crystallization, or devitrification of fused silica at elevated temperature. The rate of devitrification is sensitive to temperature, impurities in the silica, water vapor, and crystalline forms of silica existing in the amorphous structure. In the case of high purity amorphous silica it can be heated to temperatures exceeding 2300^{o} F for relatively long periods of time without significant devitrification. With increasing impurities and other silica crystalline forms the rate of devitrification increases rapidly and for materials such as technical grade slip-cast fused silica devitrification can occur in relatively short times at temperatures as low as 2150^{o} F.

Cristobalite exists in two forms, a high temperature form (β) and a low form (α). As cristobalite cools an inversion occurs between (570^{o} and 340^{o} F depending on the state of order) accompanied by a large change in volume. This causes large stresses and may result in catastrophic failure.

Solar energy is transmitted through fused silica with very little heating of the silica. By placing an absorbing coating or an absorber inside a silica tube it may be possible to transmit large amounts of energy to air flowing in the tube without heating the silica to temperatures which will cause it to devitrify.

To determine heat transfer to air a quartz tube was tested in the single tube test facility under the same conditions as the silicon carbide and cordierite tubes. Prior to testing a coating consisting of 4 weight percent (w/o) nickel oxide, 65 w/o fused silica slip, 13 w/o Ludox AS® colloidal silica and 18 w/o -325 mesh fused silica was applied to the inside of the tube by filling the tube with the mixture then allowing it to drain. The coating was dried and fired onto the tube by heating to 1350^{o} F in a furnace. This resulted in a homogeneous dark gray coating on the inside of the tube.

The coated fused quartz tube was installed in the single tube test facility. Silicon carbide "dummy" tubes were used. No thermocouples were attached because an accurate temperature reading could not be attained on the silica surface without shielding of the thermocouple junction. The Barnes I.R. pyrometer was aimed at the tube surface. Air flow through the dummy tube was at the same rate as used in the previous silicon carbide tube tests.

The data obtained are listed in Table I. Data for silicon carbide and cordierite tubes tested under approximately the same conditions are also listed for comparison purposes.

Thermal Cyclic Test Facility

As of the end of March the thermal cyclic test facility was approximately 50 percent completed. All construction materials have been received or are on order. It is anticipated that the silicon carbide tubes will be shipped about 15 April 1976. The cordierite tubes are anticipated to be shipped about the same time. Fused silica tubes have been ordered on Georgia Tech funds and these will be tested on a non-interference basis only. The thermal cyclic test facility is being constructed so that a ceramic "u" tube can be heated in the radiant zone. For those cases where a ceramic "u" tube is not available, the ceramic tubes pass through an insulating section and a metal "u" is placed on the outside of the facility. Provision has been made to use a pneumatic cylinder to apply a load to the metal "u" thus loading the ceramic tube section also.

Respectfully submitted,

Joe N. Harris
Project Director

jw

TABLE I

HEAT TRANSFER DATA FOR CERAMIC TUBES

Pressure in Tube (psig)	Preheater Output (^oF)	Flow (cfm)	Barnes IR Pyrometer (^oF)	ΔT Across Tube (^oF)
0	{500} 500 (500)	{17} 18 (21)	{1500} 1475 (1810)	{265} 385 (420)
15	{500} 490 (500)	{18} 18 (18.7)	{1350} 1300 (1550)	{202} 327 (390)
30	{500} 490 (500)	{18} 18 (18.7)	{1150} 1200 (1450)	{153} 286 (331)
60	{425} 420 (500)	{18} 18 (18)	{1000} 1125 (1250)	{115} 218 (240)
60	{500} 500 (500)	{12} 12 (12)	{1100} 1125 (1375)	{242} 240 (250)
60	{500} 500 (500)	{ 8.3} 7.8 (8)	{1150} 1150 (1450)	{176} 285 (275)
100	{480} 500	{ 8.0} 7.4	{1000} 1200	{124} 287
100	{500} 500	{ 3.6} 3.3	{1150} 1375	{242} 449

Notes:

1. Values in () are for silicon carbide active tube with silicon carbide "dummy" tubes.
2. Values in { } are for a cordierite active tube with cordierite "dummy" tubes.
3. Values not in () or { } are for a coated clear fused quartz active tube with silicon carbide "dummy" tubes.
4. All data were obtained with the tubes three inches from the modified "C" array (lamps at 280 volts), fused silica reflector in place, and dummy tubes air cooled.

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

May 21, 1976

Black & Veatch
P.O. Box 8405
Kansas City, Missouri 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 10, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design," for the Period April 1-30, 1976, Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

Studies were made of Sauereisen cements for joining of cordierite tubes. Scrap parts of tubes and discs obtained from Coors Porcelain were joined using Sauereisen #78 cement. The cemented joints were air dried overnight, then heated to 2200° F for 20 minutes then air quenched to room temperature. There was no evidence of thermal shock and the joints remained strong. Since this cement was recommended by Sauereisen for joining cordierite and the scrap pieces were not suitable for mechanical testing no further tests were conducted.

The remainder of this report period was spent in assembling the radiant thermal cyclic test facility. Delays in completion of the facility occurred because vendors of critical parts failed to meet their promised delivery dates. The key delay was in getting 400 amps of 460 volt, three phase power installed. Delivery of distribution boxes and final installation is anticipated to be completed by May 7, 1976.

The power supply for the radiant lamp facility was built up from four Research Incorporated "Tri-Phasers". These are 460 volt,100 amp, three phase silicon controlled rectifiers. One Tri-Phaser is to be used to power the 25 kilowatt air pre-heaters. The other three will each power 28 of the 1.6 kilowatt lamps. The control panel has been wired with latching relays to automatically shut off the power and to keep it off until it is manually reset if a heating overload occurs due to water or air pressure failure. Panel operation will be checked out as soon as power is available.

The quartz lamp panel containing 84 lamps and the fused silica reflecting cavity were completed. The air pre-heaters were received from the vendor, Hot Watt Incorporated, on April 30, 1976. The parts of the facility yet to be completed are the inlet and exhaust headers, and the flanges for connecting the ceramic tubes.

The Carborundum Company has experienced unanticipated problems in joining silicon carbide tubes using their brazing techniques. This may cause a long delay and tubes may not be available before June 1, 1976. The first coordierite tubes are anticipated to be available for joining and testing in early May. The fused silica tubes ordered at Georgia Tech expense are expected to be delivered by mid-May.

Based on the currently available data it is anticipated that the thermal cyclic test facility will be operational with a cordierite U-tube by May 15, 1976. Photographs of the facility will be included with the letter report for May (Interim Progress Report NO. 11)

Respectfully submitted,

Joe N. Harris
Project Director

A-1757

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

June 4, 1976

Black & Veatch
P. O. Box 8405
Kansas City, Missouri 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 11, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design," for the Period May 1-31, 1976, Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

The thermal cyclic testing facility became operational on 15 May 1976, with a cordierite U tube in place. The U tube was constructed from four straight sections of cordierite tube 2.025 OD x 1.725 ID x 22½ inches long and a U tube with a 3 inch center line radius. The U was essentially a semicircle with no straight sections on the ends. The U tube was put together with cordierite collars 2½ inches in length with a 2.515 inch OD x 2.070 ID the center ½ inch contained a shoulder with an ID of 1.725 inch which was equivalent to the ID of the tubes.

Two Sauereisen cements were used on the first U tube. Number 78 as recommended to us by Sauereisen was used for all but one joint. Number 8 as recommended by Wendel Brown at Coors was used on the remaining joint.

The procedure used in putting the first unit together was to place two collars on the open ends of the U and to fill the 0.023 inch gap between the collar and the wall of the U with Sauereisen cement. Both cements are dilatant and vibration was needed to ensure that the cements flowed to fill all areas between tube and collar. The No. 8 cement was more difficult to work with because it had a higher shrinkage and it took some time to fill the collar and have the surface remain level as it dried. Because the U tube had no straight section it was not possible to align the collars in a straight line and still have the U tube "bottomed out" against the collars. As a result the collars were tilted approximately 5 degrees on the U resulting in a non-uniform cement joint thickness around the tube.

Two collars were applied to the straight sections using No. 78 cement and then these and the U were dried overnight to allow the cement to set. A dual ring stand arrangement was used to hold the remaining sections together for joining. The U was placed with the collar ends up. The straight sections having collars attached were placed up so the ends without collars were placed in the collars on the U. The remaining two sections were placed in the collars on the other two straight sections and all joints were filled with number 78 cement. The assembled tube was allowed to dry overnight without moving; it was then placed in a kiln and heated to 1500° F to further cure the cement. The tube was then fastened to the headers by placing a tapered bolt-on collar around each tube and wrapping the tube with asbestos tape soaked in sodium silicate; as the collar bolts were tightened the asbestos tape was compressed tightly against the tube. The area between the header surfaces and the compression collars were covered with three asbestos paper gaskets soaked in sodium silicate before the bolts were put in place.

When the system was turned on two leak sources were detected. The joint made with the number 8 Sauereisen cement leaked and the compression seals made with asbestos tape leaked. The leak at the U tube was sealed by filling the pin holes with number 78 cement and building a fillet at the top of the collar. The U tube was removed from the facility and the asbestos tape at the base was removed. The taper in the collars was packed with a mixture of chopped asbestos fiber and sodium silicate and rebolted to the headers. The system was turned on and the collar at the U began to leak at about 15 psig. Therefore, a decision was made to cycle at this air flow or less.

The first cycle was run with air at 8 psig without the preheater. Time to tube surface temperature of 1360° F was 9 minutes. Exhaust air temperature reached 935° F. Cooling time to ambient was 7 minutes. The second cycle was operated at 14 psig with a low current on the preheater to bring the air to 220° F. Because of the low air flow there was a hesitancy to raise the preheater temperature for fear of a hot spot and a burnout of the windings. The tube surface reached a temperature of 1300° F in 18 minutes. Exit air reached 1000° F.

Cycle 3 was run at 14 psig air with preheat air entering the tube at 450° F. The tube surface reached 1300° F in 10 minutes. Exit air temperature was 960° F.

Cycle 4 was run at 14 psig air with preheat air entering the tube at 550° F. The tube surface reached 1550° F in 20 minutes with exit air reaching 1160° F. Sometime during this cycle the collar on the inlet side of the U cracked completely in two pieces. Failure was horizontal through the U and just below the shoulder.

In disassembling the tube exterior cracks were found running the length of the straight sections, however, these cracks were very shallow and paralleled the area where the mold parting line had apparently been ground off the tubes. All collars were removed by sawing them off the tubes.

A second set of collars was modified by grinding the shoulders out flush so that a straight through sleeve was obtained. This approach was taken for two reasons. First, the straight through collar eliminates the stress concentration point where there is an abrupt change in thickness. Second, by removing the shoulder a method is provided for field repair. With the shoulder in place tubes have to be turned over so that cement is flowed into the joint under the force of gravity. With a straight through sleeve the entire sleeve can be filled with cement from one side.

The U tube was reassembled in the thermal cyclic test facility using the following procedure. The two tapered header collars were placed on the first two straight tube sections and the tapered area was filled with the chopped asbestos fiber sodium silicate mixture. The header collars were then bolted in place over the asbestos gaskets on the headers. Tightening the collars forms a compression seal around the tubes.

A straight through sleeve was placed over each tube and allowed to temporarily slide down the tube out of the way. Number 78 Sauereisen cement was placed on the flat ends of the straight tubes and two more straight sections butted against these. After a few minutes of drying time the sleeves were slipped up the lower tubes and positioned so that they overlapped each tube by 1¼ inches. The sleeve was temporarily held in position by masking tape wrapped around the tube and the bottom of the sleeve. The entire sleeve was then filled with number 78 Sauereisen cement thinned for ease of flow.

The same procedure was used for attaching a new U section to the top of the straight tubes. The new U had 7/8-inch long straight extensions on its base (cast in one piece, not sleeves) so that there was no alignment problem with the coupling sleeves. The cement joints were cured first with the aid of heat from a standard 100 watt bulb. Then after thorough drying with an electric heat gun the tube was ready to begin cycling.

The first cycle on the modified tube was run at 14 psig. A maximum surface temperature of 1525^{o} F was reached in 6 minutes directly opposite the quartz lamps. Temperature at the same height 90 angular degrees away (directly opposite the other leg was 1515^{o} F. At 180 angular degrees (opposite the back reflector wall) was 1360^{o} F. At 270 angular degrees (opposite the side reflector wall the temperature was 1405^{o} F. The entrance preheated air was 525^{o} F and the exit air was 975^{o} F. Cooling time to ambient conditions was 10 minutes. After cooling there was a crack in the sleeve on the exhaust side of the U. This was successfully patched with number 78 Sauereisen cement and caused no further problems.

Due to the installation of a higher capacity flow meter, thermal cycles two through five were run without flowing air (lamps only). In cycle two the maximum tube surface temperature reached 1950° F after 27 minutes and cooled to 900° F in 7 minutes. In cycle three the temperature increased from 900° F to 1950° F in 5½ minutes, it cooled back to 860° F in 7½ minutes. In cycle 4 the temperature increased from 860° F to 2010° F in 9½ minutes and cooled to 900° F in 7½ minutes. In cycle 5 the tube temperature reached 1960° F from 900° in 9 minutes. The tube was then allowed to cool to ambient for restart of the air.

The air was turned on at a mass flow rate of 11 lb/min (40 psig) and the preheater temperature slowly brought up. After 8 minutes the preheated air temperature was 525° F and the tube surface had reached 425° F. At this point since there were no detectable leaks the lamps were turned on and the system ran for an additional 21 minutes. Maximum tube temperature reached 2220° F. Preheat air input was at 700° F and exit air temperature was 1160° F.

Shortly after shutdown a large air leak developed between the collar on the exhaust side of the U-tube and the header. This occurred because of the header bolts expanding and allowing the gasket to blow out. The water cooled bolts had not been used. It was necessary to remove both sides of the U tube from the facility to replace the gaskets.

The tube was reinstalled and the lamps turned on to bring the temperature of the facility up to about 350° F to be certain that the gaskets and new packing material was thoroughly dry before turning on the air. The air preheater and the lamps were turned up simultaneously. At the end of 4 minutes the sleeve on the inlet side of the U cracked completely through. At the time of failure the two thermocouples 180 angular degrees apart and just below the sleeve indicated surface temperature of 735° and 750° F respectively. The preheat air was entering at 415° F and the exit air was at 530° F. It can be assumed that the air passing through the tube at the point of the sleeve was approximately 450° F. Therefore, a 300° F temperature differential existed between the inside of the tube and the outside of the sleeve. This was much smaller than the temperature differential on the previous runs and should not be cause for thermal shock failure. The two thermocouples in the same relative position on the hot leg indicated 715° and 760° F respectively, so it can be assumed that the hot leg had not increased significantly in length to cause a bending stress on the joint. Pressure in the system at time of failure was only 40 psig. This sleeve joint was either subjected to bending stress in replacing it or it was already weakened from previous thermal stresses.

On the assumption that failure was due to thermal stress due to the thickness of the sleeves, the sleeves for the next cordierite U tube are being machined down to 1/8 inch in thickness. An alternate choice may be to use silicon carbide sleeves since the cordierite tubes have thus far survived.

Photographs of the test facility are shown in Figures 1 through 3. Figure 1 is an overall view of the radiant test facility with the U tube installed. Figure 2 is a view of the control equipment and Figure 3 is a close-up of the shortened U tube showing the sleeve failure on the inlet (right) side of the U.

The remaining cordierite straight tubes are expected to be delivered during the first week of June. The one silicon carbide brazed joint tube received thus far has been vacuum checked for leaks. One end of the tube was sealed and a thermocouple vacuum gauge placed in the other. The tube was pumped down to 5 microns pressure and the vacuum system shutdown. It required several minutes to leak to 100 microns. This was taken as an indication that the tubes and joint were sufficiently leak tight. The tube has not been tested at either elevated temperatures or pressures.

During the next report interval the new cordierite tubes will be assembled with the thinner sleeves and thermally cycled either to failure or until sufficient cycles are achieved to move to the silicon carbide. The inconel U and the air spring to hold it in place are complete. Thermal cycling of the silicon carbide can begin once the other tube is received.

Respectfully submitted,

Joe N. Harris
Project Director

jw

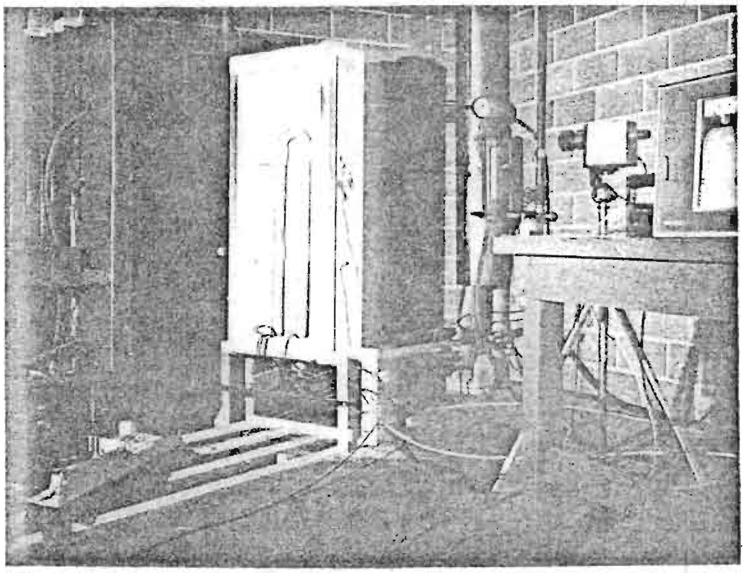


Figure 1. Overall View of Test Facility.

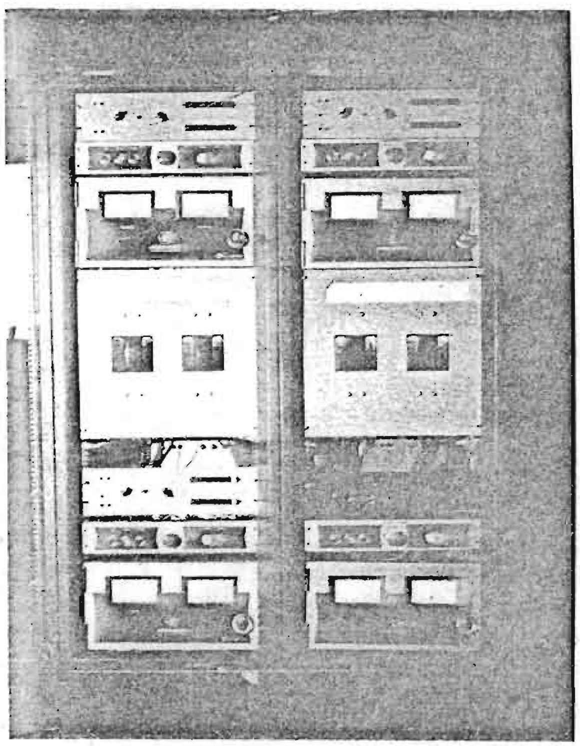


Figure 2. Control Panel.

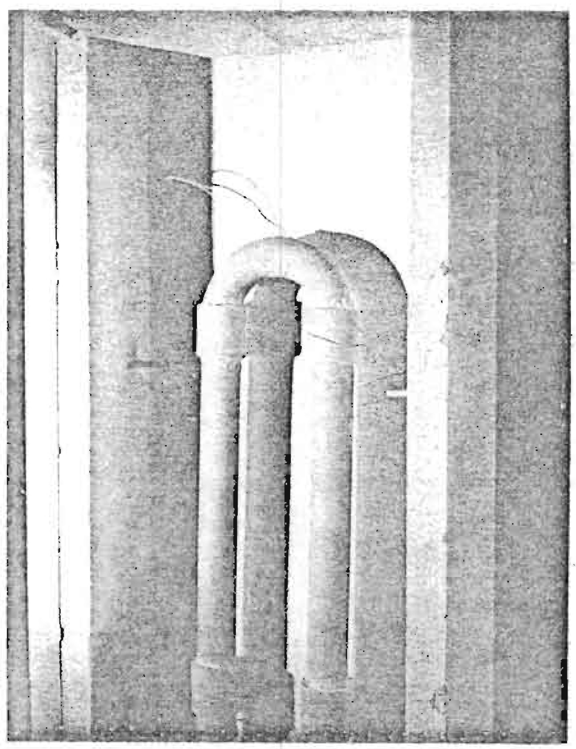


Figure 3. Close-Up of Shortened Cordierite U Tube Showing Cracked Sleeve on Inlet Side.

A-1757

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

July 14, 1976

Black & Veatch
P. O. Box 8405
Kansas City, Missouri 64114

Attention: Dr. J. C. Grosskreutz, Project Coordinator

Subject: Interim Progress Report No. 12, "Solar Thermal Conversion to Electricity Utilizing a Central Receiver, Open Cycle Gas Turbine Design," for the period June 1-30, 1976. Black and Veatch Project 6983, Georgia Tech Project A-1757

Gentlemen:

A cordierite tube assembly was prepared using the old straight sections from the old assembly and the straight through cordierite sleeves which had been machined down to a wall thickness of 1/8 inch. The U tube assembly was put together with Sauereisen #78 cement using the same procedure as the previous assembly. After the cement had thoroughly hardened, air pressure was turned up until the pressure reached 55 psig. The mass flow of air was 11 lb/minute. Preheat air temperature was 530°F and exit air temperature was 1000°F at the end of the run. The external temperature was increased slowly by incremental increases of power to the lamps. At 15 1/2 minutes after the start of the run the straight tube on the inlet side exploded taking out about six inches of tube. The missing portion of the tube was about one foot above the base of the heated area. The reason for the tube failure was not apparent. The circumferential temperatures on the opposite leg are shown in Figure 1. The positions, correspond to thermocouples 7, 17, 19 and 21 in Figure 2. Readings for thermocouple 1 which was on the section that broke are shown as solid dots on Figure 2. All recorded temperature data are given in Table II.

The remainder of the time during this report period was spent on preparation of the Final Report Draft and in preparation for the EPRI Quarterly Review in Kansas City.

The second silicon carbide straight tube was delieverd on 25 June 1976. It is anticipated that thermal cycling of the silicon carbide tubes joined by an Inconel U-bend tube will be initiated during the month of July.

Respectfully submitted,

J. N. Harris
Project Director

jj

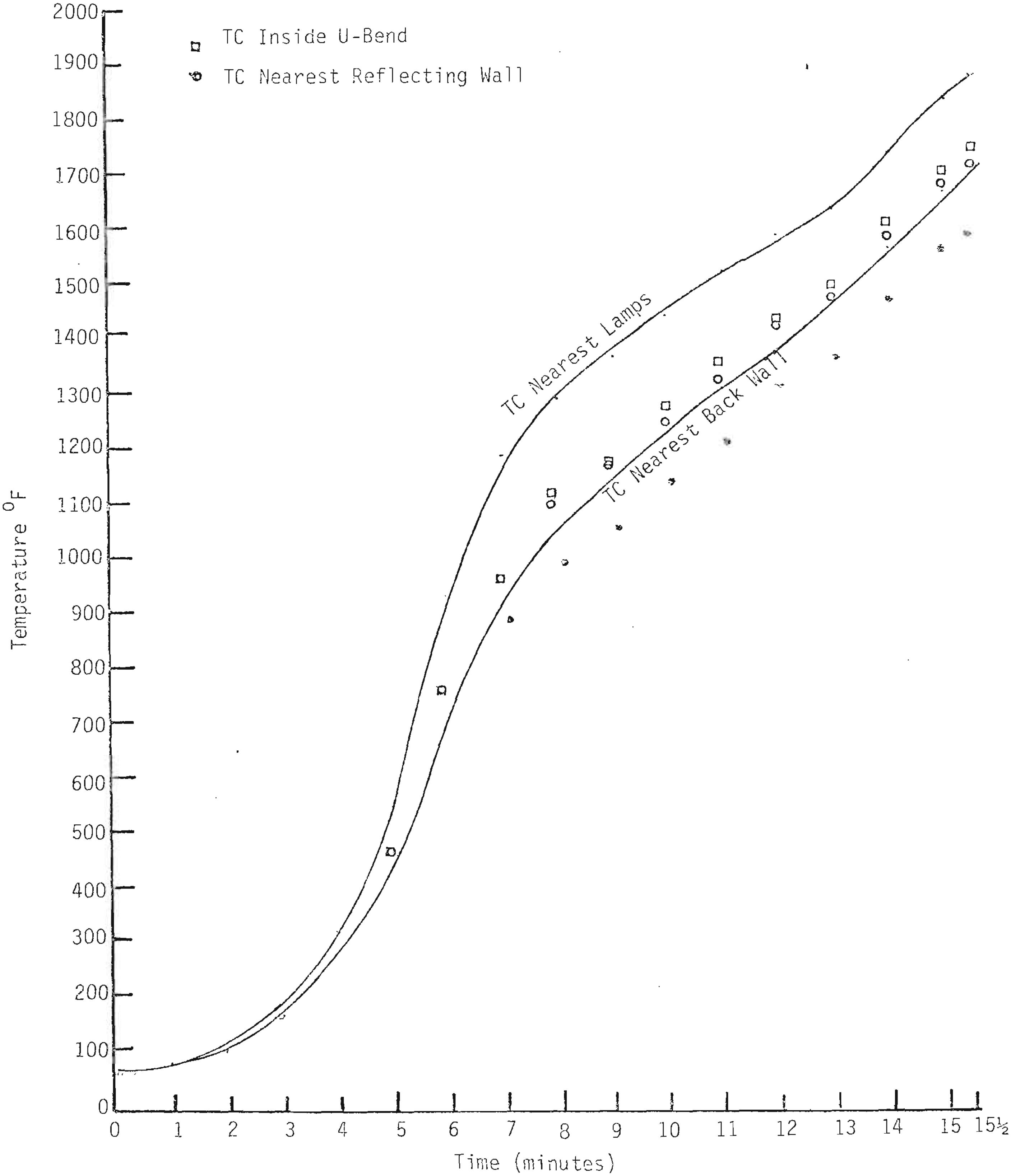


Figure 1. Temperature Distribution on Cordierite Tube at 90 Anglular Degree Intervals.

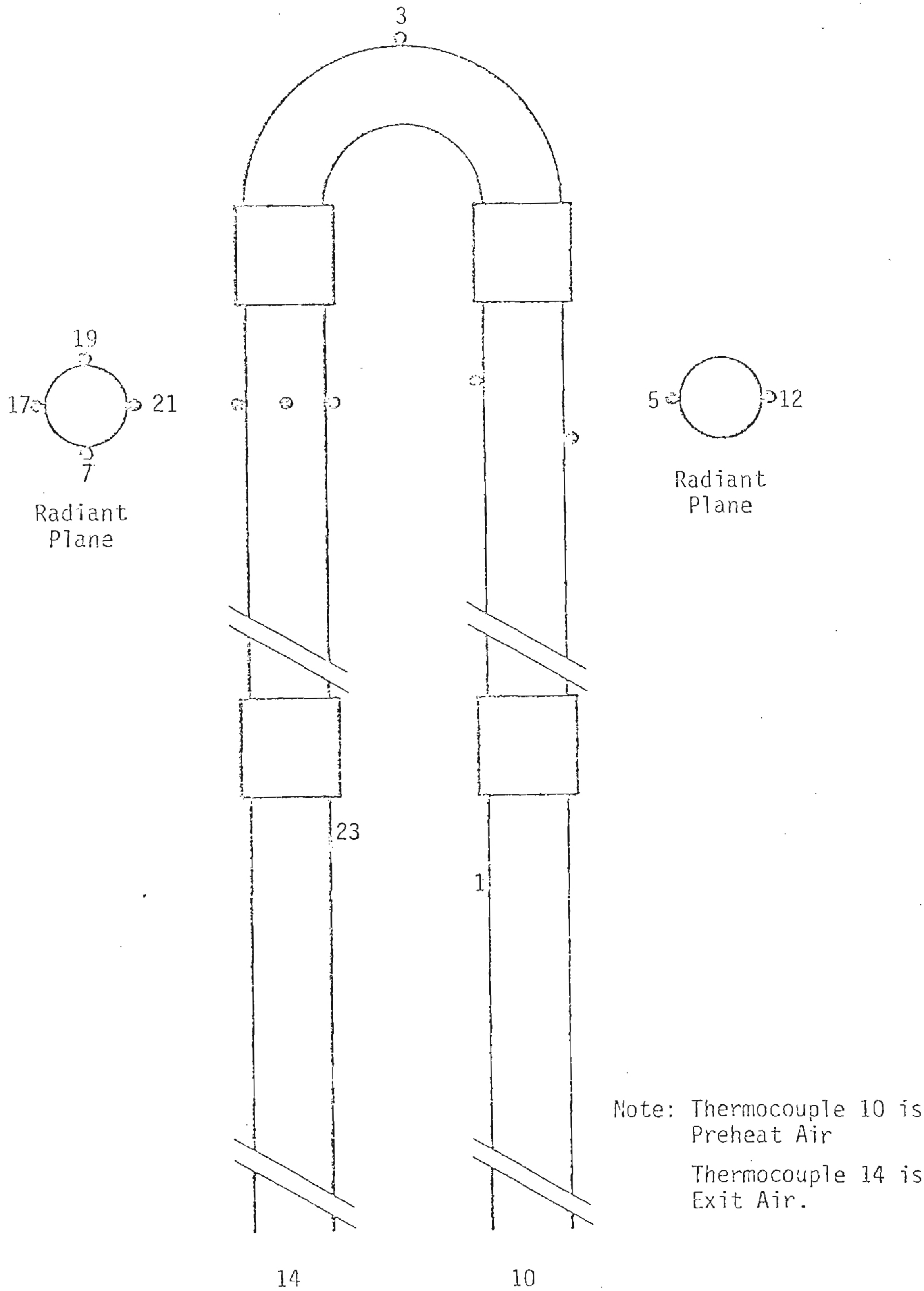


Figure 2. Thermocouple Locations on Cordierite Tube.

TABLE I

TEMPERATURE DATA FOR CORDIERITE TUBE DURING FAILURE CYCLE

Time (min)	Input Air (°F)	Exit Air (°F)	TC 1 (°F)	TC 5 (°F)	TC 12 (°F)	TC 3 (°F)	TC 7 (°F)	TC 19 (°F)	TC 17 (°F)	TC 21 (°F)	TC 23 (°F)
1	175	---	---	---	---	---	---	---	---	---	---
2	215	---	130	130	130	130	130	130	130	130	130
3	245	280	170	170	170	170	170	170	170	170	170
4	290	325	280	280	270	340	325	275	275	250	225
5	290	375	440	475	450	570	550	450	450	450	450
6	430	545	730	800	760	975	925	730	760	760	760
7	500	670	880	1010	950	1165	1180	920	960	955	940
8	520	740	950	1150	1075	1285	1285	1050	1085	1120	1070
9	530	775	1040	1225	1170	1350	1360	1125	1170	1175	1130
10	540	810	1125	1320	1260	1470	1430	1225	1240	1270	1225
11	540	845	1210	1390	1335	1560	1510	1310	1315	1350	1290
12	535	880	1290	1470	1415	1620	1575	1375	1410	1425	1375
13	535	895	1340	1510	1450	1660	1625	1440	1460	1475	1430
14	535	930	1450	1620	1570	1800	1725	1555	1570	1600	1545
15	535	980	1525	1710	1680	1920	1825	1660	1670	1690	1620
15½	535	1000	1970	1760	1730	1960	1870	1700	1700	1730	1640